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RESONANT RADIATION AND MOVING STRIATIONS IN AN ARGON GLOW DISCHARGE

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RESONANT RADIATION AND MOVING STRIATIONS IN AN ARGON GLOW DISCHARGE

by

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ABSTRACT

A study of the argon glow discharge, to include determining the discharge conditions for maximizing the intensity of 8115A^{o} radiation; observing the effects of external radiation and the absorption of the 8115A^{o} line was conducted. Discharge tubes having diameters of 25 and 35 mm, with gas pressures in the range of 0.5 mm to 13.0 mm Hg were used. The intensity of the 8115A^{o} line was observed to increase with increase in current and pressure. A small increase in frequency of moving striations was observed when the glow discharge was irradiated with another argon glow discharge, but no increase was noted when the 8115A^{o} radiation passed through the discharge. No changes were found in striation wavelength, amplitude or the discharge potential, when the main discharge was subjected to radiation composed of the entire argon spectrum, or to single line irradiation with 8115A^{o}. The results of the absorption experiment indicate that there is more attenuation of the beam of 8115A^{o} radiation when the main discharge is operated at low currents than at high currents. This may correspond to a denser population of $4S_{12}$ metastable atoms at low currents than at high currents, which would indicate a strong dependence of moving striations on metastable concentrations.

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1. Introduction

1.1 Background

Since the latter part of the 19th century many studies have been made of direct current glow discharges in the rare gases and mercury vapor. Wüllner in 1874 reported the presence of moving striations in the positive columns of glow discharges [1]. Many investigators have studied the phenomenon of moving striations since their discovery, yet today, no adequate theory exists to explain their existence or properties. The classical approach to an explanation of moving striations has been to use the theory of plasma oscillations. This approach has had little or no success. Gas discharges and their instabilities have assumed a position of extreme importance in recent years. The large scale research in plasmas in connection with reentry and space physics, thermonuclear fusion and quantum electronic devices (eg. lasers) has aroused great interest in plasma instabilities, of which the moving striations in the glow discharge positive column are probably the best known but least understood example. The phenomenon of moving striations in low pressure discharges is probably the instability most familiar to plasma physicists, yet the well-known texts conspicuously avoid the subject, or refer simply to the empirical data. This is not too surprising because every few years there appeared a new attempt to explain the phenomenon of moving striations. The subject of moving striations is a difficult one because several forms of striations do occur and their properties are quite sensitive functions of the discharge parameters. Other oscillations, such as anode oscillations and voltage oscillations, occurring in the discharge may cause intermodulation. In recent years, notable advances in explaining moving striations have been made by A. W. Cooper, L. Pekarek, H. S. Robertson, N. L. Oleson, and K. Wojaczek.

Moving striations are a common phenomenon. They are present over a wide range of currents, pressures and discharge tube sizes. Even in a normally striation free regime, they may sometimes be induced

by external radiation, by other oscillations, and by the application of external electric or magnetic fields.

1.2 The Glow Discharge [2]

An applied voltage to a discharge tube having a pressure of a few millimeters of mercury produces a glow throughout the major part of the tube. This glow discharge consists of alternate dark and light regions. These regions are not to be confused with standing or moving striations that are found in the positive column, which is one of the light regions of a glow discharge. It is produced by electron transitions in atoms and ions excited by electron collisions. The width and relative intensity of the characteristic dark and light regions are dependent upon the tube geometry, gas pressure, applied voltage, discharge current and type of gas. Standing immediately in front of the cathode and proceeding to the anode, the following regions have been identified: Aston dark space, cathode glow, cathode dark space, negative glow, Faraday dark space, positive column; anode glow and anode dark space. The positive column is a long glowing region which fills most of the length of the discharge tube. The dark spaces are not absolutely devoid of light but are dark only relative to the bright glowing regions where ionization processes are much more active. If the gas pressure is reduced, the negative glow and the Faraday dark space appear to expand at the expense of the positive column until at a sufficiently low pressure the positive column disappears completely. A similar effect is noted if the electrodes are moved together at constant pressure and current. The phenomena at or near the cathode are essential to the discharge and characteristic of the current and pressure conditions, and the positive column merely serves to maintain a conducting path for the current. The approximate characteristics of a glow discharge are shown in Figure 1.

There are three kinds of glow discharges, the normal, subnormal, and abnormal discharge [3]. If a discharge is maintained between two plane electrodes at a pressure of about one torr, the potential

drop across the tube as a function of current is as shown in Figure 2. Note the constant voltage drop over a current range of a few orders of magnitude. The current density at the cathode remains relatively constant while the effective area of the cathode changes. This is the region of the "normal" cathode fall in potential. When the current is reduced until the cathode area of the discharge has a diameter of the order of the thickness of the cathode dark space, the cathode fall increases. This is due to the fact that as the diameter of the discharge becomes small, more charges will diffuse radially outwards and be lost due to recombination. The current density at the cathode decreases and fewer electrons are emitted from the cathode. A larger cathode fall is required to maintain a steady state. This is the region of the "sub normal" cathode fall. The discharge is often intermittent. At larger currents, when the whole cathode surface appears to be covered by the glow, an increase in current can only be obtained by an increase in current density. A larger cathode emission is necessary, and this again increases the cathode fall. Small changes in cathode fall are here associated with large changes in the current. This is the region of the "abnormal" cathode fall.

The positive column is so called because it connects the negative zones to the anode. It is bounded on the negative end by the Faraday dark space and on the other end by the anode glow. The axial electric field gradient $\frac{-dV}{dX}$, in the positive column can be found by observing the potential difference between two probes places at the known distance apart, or by reading the voltage across the discharge for constant current and varying electrode distance. It has been found that $\frac{-dV}{dX}$ = constant, therefore $\frac{d^2V}{dX^2} = -4\pi(\rho^+ - \rho^-) = 0$: hence the number of positive and negative charges per unit volume or per unit length of column are equal. In the steady state uniform positive column, the electric field must have such a value that the number of electrons and ions produced per second just balances the loss of

charge. The current in the positive column is carried mainly by electrons because of the small mobility and drift velocity of positive ions. The positive column is a typical example of a plasma. Stationary or moving striations and plasma oscillations are found in rare as well as molecular gases [4].

The ionization and excitation processes taking place in a glow discharge are of such importance that a review of these processes is deemed necessary. An atom is said to be excited when an electron is lifted from a lower to a higher energy level. This increase in energy may be due to the interaction of the electric field of an incoming electron or ion, or even to mechanical collisions, especially by fast neutral particles. Excitation may also occur when a quantum of radiation of the correct energy is absorbed by the atom. If the energy given to the atom by any of the above means is greater than the ionization potential of the atom, ionization will occur; if less, excitation or elastic scattering occurs. The electron in the higher energy level will remain in that state for about 10^{-8} seconds, before falling to a lower state with the emission of radiation having a frequency, ν, given by the equation

$$\nu = 2\pi^2 \frac{me^4}{h^3} \left(\frac{1}{n_2^2} - \frac{1}{n_1^2} \right)$$

where n is the principal quantum number and $n_2 < n_1$. This is called spontaneous emission. The electron may, however, be excited into a state from which it cannot fall spontaneously, or at least the probability of such a transition is very small. This is a metastable state, and a transition to a lower state would break one of the selection rules.

$\Delta L = \pm 1, 0$; $\Delta S = 0$ or $\Delta J = \pm 1$ or 0, but not $J = 0$ to $J = 0$.

Metastable states can last in excess of 10^{-2} seconds, but in most discharge conditions they are destroyed within this time. Metastable states are usually found among the lower energy levels, since there

are few even lower levels into which the electron can fall. The metastable atoms found in the discharge have been linked to moving striations. The problem still exists, however, of determining more exactly the influence of metastable atoms in the excitation of moving striations. While perhaps not always necessary for all striations, there is much evidence to show that metastables play an important role in the initiation of at least one kind of moving striations.

1.3 Previous Experimental Work

Scientific literature began to show experimental observations on moving striations as early as the latter part of the nineteenth century. From that time forward until about 1930, many investigators published their observations on moving striations. Cooper [6] gives a very concise resume of these historical works. In the early 1930's, W. Pupp [5] presented a series of papers containing his observations of moving striations. Movable photo-cells, an oscilloscope, rotating mirror, and an oscillator seem to have been Pupp's primary investigative tools. Pupp's works have been summarized in the publications of Francis, Penning, Druyvesteyn and others. A few observations of interest to this investigation will be summarized here. In Pupp's first paper, he describes the technique of measurement of the frequency, wave length and, thus, velocity of moving striations, using two movable photo-cells in conjunction with oscilloscope traces. This same technique was used in this investigation to observe the relationship between these basic striation parameters and current and pressure. Also reported were critical currents for disappearance of moving striations as a function of pressure. Pupp concluded that moving striations and anode oscillations were independent phenomena and that moving striations were produced within the positive column. Pupp also described a technique for preventing anode oscillations by setting up an auxiliary discharge at the anode.

Few investigations of moving striations were made during the period 1935 through the end of World War II. In 1949 and again in 1951,

Donahue and Dieke published their observations on moving striations in inert gases [7, 8]. They concluded that negative striations originate in the negative glow region near the cathode and are triggered by approaching positive striations. The positive striation were thought to have been caused by a build-up of a cloud of ions near the anode which was released simultaneously with the occurence of a maximum in tube potential. They also concluded that moving striations and oscillations were normally present in the positive column of inert gases and that lack of them is an unusual occurence. Zaitsev published papers in 1951 and 1952 which are summarized by Cooper [6]. The conclusions drawn by Zaitsev that anode osciallations and moving striations are not independent instabilities was contrary to Pupp's earlier observations. Experiments conducted by Cooper [9] on the origin of moving striations and published in 1964 agree with Pupp's work. He investigated the origin of moving striations by measurement of striation propagation parameters at a sharp change in tube diameter, by a study of the relationship between anode spot oscillations and moving striations, by observation of anode spot oscillations at or above the cut-off current for moving striations, by use of Pupp's auxiliary discharge technique for suppressing anode potential oscillations and by study of a striation system isolated from the electrodes. The results of these experiments are:

a. The striation frequency, velocity, and wavelength all change discontinuously at a change in tube diameter.

b. Visible spot oscillations are accompanied by oscillations in discharge potential, and exist unchanged above the critical current for disappearance of moving striations.

c. Anode oscillations and anode spots may be suppressed by operating an auxiliary discharge to the anode.

d. The striation frequency synchronizes to an applied frequency if it is close to a small integral multiple of the natural striation frequency.

e. A striation system can be maintained in a vessel separated

from the electrodes by narrow tubes operated above the local critical currents for moving striations. No oscillations were detected in the isolating regions either photoelectrically or with electrostatic probes.

Cooper concluded that anode oscillations and moving striations are independent phenomena. He further concluded that moving striations do not constitute the response of the discharge to an external disturbance, but seem to result from a local instability in the positive column. These experiments are believed to be the most rigorous and conclusive in showing anode oscillations and moving striations as independent phenomena. Cooper and Oleson [10] reported in 1961 the results of their experiment on critical currents for moving striations. From rotating mirror photography they showed that there is no unique critical current at which striations disappear simultaneously from the whole column but disappear progressively from the cathode end. They concluded that the presence or absence of moving striations not only depends on pressure and current but also on local tube diameter and distance from the cathode.

Meissner and Miller [11], L. Pekarek [12], and Mischke and Schmidt [13], reported their results of external radiation on glow discharges of various inert gases. Meissner and Miller found that by irradiating He, Ne, A, and Xe discharges with discharges containing the same gas, there is a definite increase in the discharge tube potential in each case. Mischke and Schmidt found that in general, the striation light intensity was decreased throughout the positive column with increasing illumination intensity, the decrease always being greatest where the potential increase was greatest. In fact they were able to destroy the striations within the detection capability of their equipment with sufficient illumination. This destruction occurred in regions of the discharge tube where the potential increase exceeded about 12%. Pekarek found that external illumination of a discharge in neon with light of the same spectral composition, caused an increase in the tube potential, a decrease in the striation wavelength, and an

increase in the striation velocity.

In February 1964, Sicha, Vesely, Studnicka and Prostejovsky [14] published some notes on the excitation of moving striations in the anode region. They made an experimental study of the propagation of moving striations in the positive column of a neon glow discharge. Their results agreed with the hypothesis of Emeleus, Armstrong and Coulter that fast striations propagate towards the anode; and for self-excitation the feed back through the external circuit is essential. Kenjo and Hatta [15] in December 1964 reported that the wavelength of moving striations is experimentally proportional to R^n where R is the tube radius and the exponent n ranges from 1.5 to 2.0. The measurements were made using tapered discharge tubes, in which the ionization frequency varies continuously along the tube. A theory is also introduced by these investigators, which in their opinion, gives a general explanation of moving striations. This theory will be mentioned later in this paper.

1.4 Previous Theoretical Work

For any theory to be widely accepted it must explain the presence of moving striations and predict their behavior in terms of basic plasma parameters. Theoretical studies have generally treated the phenomenon as a periodic perturbation of the stable homogeneous positive column. This perturbation has often been considered as a local oscillation in plasma potential or density. The theoretical works of Langmuir, and Tonks, Druyvesteyn, Gertzenstein and Potemkin, Stewart and others are adequately summarized by Cooper [6] and will not be discussed here. Coulter, Armstrong, and Emeleus [17] postulated that moving striations are caused by oscillating anode spots "stripping off" from the electrodes. Donahue and Dieke also believed that moving striations originated in regions near the electrodes. Oleson and Watanabe [18] showed that traveling waves of ion and electron densities can exist in the positive column. They did not attempt to identify these waves as moving striations. By the use of diffusion equations they

sought to establish mathematically the possibility of these ionization waves in the positive column of a glow discharge. Loeb [19] believed that the cathode was the seat of oscillations which might initiate striations.

Two of the most recent attempts to explain moving striations have been presented by Kenjo and Hatta [15] and Alexeff and Jones [16]. Kenjo and Hatta derived a dispersion relation in which the wave number, α, and the propagation constant, β, were defined by the relations,

$$\alpha = \frac{4\ \omega_o\ \omega\ \xi}{\omega_o^2 + (3/2)^2\ \omega^2}$$

$$\beta = \frac{(3\ \omega^2 - 4\ \omega_o^2)\ \xi}{2[\ \omega_o^2 + (3/2)^2\ \omega^2]}$$

where ω_o is approximated by $\frac{5.78\ Ei\ \mu i}{q\ R^2}$ with E_i being the ionization potential of an electron, μ_i the ion mobility, q the electronic charge, R the tube radius, ω the angular frequency of moving striations and ξ the ratio of the initial electric field to the initial electron temperature. From the above equation an expression showing the relationship between the striation phase velocity and group velocity was shown as

$$V_{gr} = \frac{\partial \omega}{\partial \alpha} = V_{PL} \quad \frac{\omega_o^2 + (3/2)^2\ \omega^2}{\omega_o^2 - (3/2)^2\ \omega^2}$$

A necessary condition for the appearance of waves is that $\beta < 0$ and $V_{gr} < 0$. This condition is satisfied if

$$2/\sqrt{3}\ \ \omega_o > \omega > 2/3\ \omega_o$$

The waves which appear under this condition are believed to be the moving striations. The authors reported that they are backward waves (i.e. group and phase velocities are oppositely directed) which seems to agree with other findings. This theory is limited to only the backward waves, and does not make mention of those moving striations which appear to be forward waves. The theory is, admittedly, an approximation

and is not substantiated in all cases by their experimental data.

Alexeff and Jones modified the theory of ionic sound waves to include the effects of ion-gas-atom collisions. Their theory predicts that ion waves should be slowed down, as well as strongly damped by the collisions. Some quantative agreement was found between the ionic sound wave velocity predicted by the theory and the experimentally observed average velocity of the moving striations. Experimentally the strong damping predicted by the theory was not observed. The failure to observe the strong damping was believed to indicate that some mechanism is operative, especially at high pressures, which restores energy to the waves as they propagate down the tube. Hence this theory is incomplete since it does not provide for the energy restoring mechanism. Many theoreticians object strongly to the attempts to explain moving striations on the basis of ionic sound waves, since this includes trying to interpret non linear wave phenomena in plasmas in terms of a linear theory.

Perhaps the most notable theories of moving striations are those suggested by Pekarek and Robertson. In Pekarek's first theoretical study [20] he suggested that the basic dynamic process determining the low-frequency oscillation properties is a process of the gradual stratification of the plasma which denotes the beginning of moving striations. He disputes the identification of the moving striations with longitudinal electric waves in the plasma. It is claimed that the appearance of periodic structure of plasma, (i.e. moving striations, fast and slow) is connected with a heightening of the electron concentration at the cathode end of the column, which leads to an increase in ionization in that locality. The electrons emerge more rapidly than the positive ions and a positive charge is left in the locale of increased ionization. This positive space charge induces an electric field which retards electrons to the anode side giving a region of reduced ionization. An electric field is established, the electron temperature increases and ionization again increases. The

process continually repeats itself leading to the stratification of the positive column. Pekarek proposes that fast striations are the result of direct ionization of atoms by electrons, and slow striations are connected with step wise ionization involving metastable atoms. Pekarek published his theory of the successive production of moving striations in 1957 [21] . The stratification of a plasma is interpreted as the repetitive creation of regions with an alternately positive and negative space charge. This theory assumes the relative independence of the chain of events occurring in each dark or light region of the striations, thereby implying that interaction between the regions occurs only as a result of the electric field of the space charge in the neighboring region. He derives equations expressing the chronological order of the processes leading to the production of a space charge in each region. Pekarek and Krejci [22] attempted in 1962 to use as a base for Pekarek's previous theory of moving striations a partial integro-differential equation which is derived from the equations of continuity, the Laplace-Poisson equation, and the relation between the electric field and the electron temperature. This equation also includes the processes defining the electron Debye length, the influence of the deviations in concentration of electrons on the rate of production of current carriers, and the influence of the deflections on the motion of current carriers.

Robertson's theory [23] involves a new approach to the problem. By studying the detailed ion balance equation, he found that under certain conditions in the presence of step-wise ionization a stable homogeneous plasma could not exist. By making a few assumptions and simplications, the balance equations for electrons, positive ions and metastable atoms were presented in the form

$$\dot{N} = F_1(N) + MF_3(N) + \tfrac{1}{2}\alpha_1 M^2 - \gamma N - \alpha NP$$

$$\dot{P} = F_1(N) + MF_3(N) + \tfrac{1}{2}\alpha_1 M^2 - \gamma P - \alpha NP$$

$$\dot{M} = F_2(N) - MF_4(N) - \alpha_1 M^2 - \nu M + \beta\alpha NP$$

where $\dot{N}$, $\dot{P}$, and $\dot{M}$ are the time rate of change of electron concentration, positive ion concentration and metastable atom concentration, respectively, $F_1(N)$ portrays direct ionization by electrons, $F_2(N)$ represents production of metastable atoms by electron collision, $MF_3(N)$ the ionization of metastable atoms by electron impact, $MF_4(N)$ loss of metastables by electron impact, not leading to ionization, $\alpha_1 M^2$ the ionization of metastables by collision with metastables, γN and γP denote losses to the walls, νM the loss of metastables to the walls and collision de-excitation and αNP, loss due to recombination. Defining equilibrium by $\dot{N} = \dot{P} = \dot{M}$, and assuming that $N_0 = P_0$, this equilibrium state was shown to be unstable when

$$F_4 + \nu + 2\alpha_1 M + \gamma + \alpha N - \frac{dF_1(N)}{dN} - \frac{MdF_3(N)}{dN} < 0$$

Further assuming F_1 to be a monotonic decreasing function of N, all terms of the inequality are positive except

$$\frac{MdF_3(N)}{dN}$$

Thus in order for this inequality to hold in all conditions, a high concentration of metastable atoms, such as might be expected in noble gases, is necessary to produce instability. This is the first mathematical approach which specifically includes metastable concentrations.

1.5 The Role of Metastable Concentrations

There has been much evidence to support the role of metastable atoms in moving striations [13]. Kenty [24] reported his study of the role of the metastable ($^3P_2$) mercury atom in low current discharges. He noted that intense illumination of the mercury glow discharge with a second mercury glow discharge nearly suppressed the moving striations, doubled the electron temperature and tube potential, and doubled the intensity of the 2537A^O lines. These effects were explained on the basis of destruction of metastable concentrations by resonant radiation. This implied a direct connection between the

metastable mercury atoms and moving striations. Donahue and Dieke [8] suggested a two step ionization process involving metastable atoms. They proposed this process as an explanation of the phase lag between the excitation of the 2437A° line and the 4358A° line observed in moving striations in mercury.

Pekarek [12] in his study of the influence of external illumination on moving striations in neon observed changes in the basic striation parameters of both slow waves (positive striations) and the fast waves (negative striations) when the discharge was illuminated with radiation of the same spectral composition. An increase in amplitude of the negative striations and a decrease in the amplitude of the positive striations were also observed. It is concluded that his suggestion that positive striations are connected to a stepwise ionization process involving metastables, while the negative striations are related to direct ionization, is supported by this evidence.

Hakeem and Robertson [25] studied the vapor plasma of potassium, cesium and rubidium for moving striations. None of these plasmas has metastable states, and no moving striations were observed. Anode spot oscillations were observed. These were noticed to be attenuated within 1cm of the anode. These investigators later observed the effects of irradiative depopulation of metastable atoms in neon [26]. By using a second neon discharge, to irradiate the first, they were able to produce moving striations when initially no striations existed. Also using this technique, they were able to suppress striations.

Mischke and Schmidt [13] studied the effects of resonant radiation on moving striations in an argon glow discharge. They concluded that metastable atoms in argon exerted a great influence on the behavior of moving striations. This conclusion was substantiated by the increase in the tube potential when the discharge was illuminated with the resonant wavelength necessary for depopulation of the metastable states of argon. They further supported this conclusion with evidence that the moving striations were most sensitive to resonant

radiation in the regions where the potential increase was greatest.

These same investigators undertook to determine the metastable concentration of the metastable $4s_{12}$ state in argon, by irradiating their experimental discharge tube with the 8115A° line from a second source. Their sources included a tungsten filament lamp, and an argon spectral tube excited with DC power and with a 45 Mc Rf oscillator. They reported inconclusive results. Lack of an intense 8115A° line and the use of monochomators instead of an interference filter to select the desired line are believed to have been the major reasons for their lack of success.

Varnadore [27] attempted to study the same problem as Mischke and Schmidt, but used as his illuminating source, another argon glow discharge. He again used a monochromator to select the desired wavelength. He also reported inconclusive results, the major reason being attributed to lack of 8115A° line of sufficient intensity.

In spite of the lack of success of the above mentioned investigators, experiments were again undertaken by the present author to study some of the basic parameters of moving striations in an argon discharge, including an attempt to study metastable populations by the absorption technique first used by Mischke and Schmidt [13].

2. Experimental Apparatus

2.1 Discharge Tubes

Three basic designs of discharge tubes with several electrode configurations were used. Figure 3 shows these various constructions. The filaments and cylinders in tube A were arranged for the operation of an auxiliary discharge at either end, however the left end had only a single oxide coated filament while the right end contained two 20 mil tungsten wire filaments, connected in parallel for increased tube life time. Tube A is the main experimental tube. Tube B contains four pairs of tungsten filaments, the side arms having 14 mil tungsten wire and the ends having 30 mil tungsten wire. This tube was the least used. Tube C contained single 20 mil tungsten wire filaments

and is not designed for operation of an auxiliary discharge. Tubes D and E have the same shape but different electrode configurations. Tube D was designed for cold cathode operation at low currents (0-200 Ma). Tube E was designed for hot cathode operation at low to high currents (0-2.3 amps). An auxiliary discharge could also be operated at the anode. Tube E was used as the irradiating source in the metastable concentrations experiment.

2.2 Vacuum System

A schematic of the vacuum system used is shown in Figure 4. This system was a semipermanent fixture and was used in conjunction with tubes A, B, and C. Tubes D and E were evacuated with a more portable system having the same general configuration as the more permanent one. The systems were of glass and the discharge tubes were operated while isolated from the rest of the system with stopcocks. A three-stage oil diffusion pump, backed by a mechanical fore pump evacuated the discharge tubes, a manifold, and the pressure measuring device. Two traps cooled with liquid air were used, one between the manifold and the pumps, the other between the manifold and the discharge tubes. The gas was metered through two stopcocks in series. Base pressures of the order of 10^{-6} mm Hg were attained and measured with a Consolidated Electrodynamics Corporation Ionization Gauge, type DPA-38 with a VG-1A sensing tube. Gas pressure in the tubes after filling was measured on an octoil-s manometer (1 cm of oil equals 0.672 mmHg). The entire system contains large volumes and some constrictions, however it offers the advantages of quick tube changes and bake out. These are extremely valuable assets to a neophyte researcher.

2.3 Electronic Circuits

A schematic of the general circuits used is shown in Figure 5. A Kepco, model 770B, voltage regulated dc power supply, having a range of 0-2.3 amps, 600 volt maximum output was used for the main discharge tube. A Kepco, model 605, voltage regulated dc power

supply, having a range of 0-500 ma, 1000 volt maximum output was used to operate the auxiliary discharge. The filaments were normally heated with a Kepco, model Ko-45-30M, dc regulated power supply having ranges of 0-30 amps, 0-50 volts. The source discharge tube was operated with the same type of power supply as was used for the main discharge tube.

The variable resistors shown were all capable of carrying high currents (540-2300 ma). For the wide current ranges investigated, variable resistance from 409 to 10,000 ohms were used. Currents were measured with Weston current meters of the appropriate range. All tube potentials were measured with a Phaostron Company multimeter (having a high input impedence). The photomultiplier tube used was the RCA 7102. High voltage was supplied by a Pacific Designs Inc. high voltage regulated power supply, model HV-1565, with a range of 0-2000 volts, 0-15 ma. A discussion of the photomultiplier tube will be presented in the following subsection. A Tektronix 541 oscilloscope and Hewlett Packard decade amplifier were used in conjunction with the phototube. Frequencies were measured with a Hewlett Packard electronic counter, with an occasional check from oscillographs taken with the Dumont Oscilloscope Camera.

2.4 Optical Equipment

The optical equipment used in these experiments includes a rotating mirror, two interference filters, two photomultiplier tubes, Dumont oscilloscope camera, a Bausch and Lomb monochromator, and a Gaertner Scientific Corporation comparator micrometer.

The rotating mirror used for visual observation of the striations is the one used by Cooper [6]. The mirror consists of a 6"x4"x1" stainless steel block, machined and fitter with a pressed fit axle. One surface was polished to a smoothness of one quarter of a wavelength of sodium D light, and coated with an evaporated aluminum layer, which was then covered with a dielectric film to reduce pitting. The mirror has a continuous range of speeds from 0 to 9250 revolutions

per minute, with a constant motor speed. The entire assembly is balanced for rotational speeds up to 10,000 revolutions per minute.

Two p-type interference filters, peaked at 8115A^{o} ±5A^{o} were used to select the 8115A^{o} line for all of the experiments. These inch square filters have a band width of 10-20A^{o}, with 50% minimum transmission.

The photomultiplier tube used was an RCA 7102, head-on type of tube, which is intended for use in the detection and measurement of low-level red and near-infrared radiation. The spectral response of the 7102 covers the range from about 4200 to 11000 angstroms as shown in Figure 6. Maximum response occurs at approximately 8000 angstroms. The tube was operated with a high voltage of 1000 volts. The signal output from the photo tube was sent to the oscilloscope, in which a 10 K-ohm fixed resistor was in parallel with the oscilloscope input terminals. The best signal-to-noise ratio is obtained with a supply voltage in the range from 1000 to 1250 volts. Within this range, the noise at the anode is produced primarily by the statistical release of thermal electrons (dark current noise). In applications where the maximum gain with very low dark current is required, the use of a refrigerant is recommended to cool the bulb of the 7102. Thermionic emission is then reduced which lowers the detection threshold for better results. Dark current is reduced by about 50% for each 6°C reduction in temperature beginning at 25°C. The 7102 was cooled by dry ice held in the type of container shown in Figure 7. Light noise is the random release of electrons from the photocathode due to incident photons. It is proportional to the square root of the incident light intensity and is negligible compared to the dark current.

The Dumont oscilloscope camera, with Polaroid-Land type 47 (A.S.A. 3000) film, was used to photograph those oscilloscope displays deemed important to these experiments.

3. Experimental Procedures

3.1 Theory

Excited atoms usually have life times of the order of 10^{-8} seconds. Dipole transitions to lower states, with the emission of photons then occur. Atoms in metastable states are forbidden by the selection rules to make dipole transitions to lower states. The mean lifetimes of metastable states are usually of the order of 10^{-3} seconds, however in some elements, metastable life times may be on the order of seconds. The mean metastable life time for argon in the normal glow discharge is approximately 3.5 milliseconds [11]. The excited states of argon are shown in Figure 8. The two argon metastable levels, the $4s(1\frac{1}{2})$ and the $4s'(\frac{1}{2})$, are indicated with an asterisk. Optical transistions associated with these levels are shown in Figure 9.

Metastable states may be depopulated if radiation, having the discrete photon energy corresponding to the energy difference between the metastable and a higher excited state, is absorbed by atoms. The metastable atoms are then excited to these higher excited states from which a dipole transition to the ground state is allowed. This transition may be direct or by way of an intermediate state. A study of Figure 9 reveals that a beam of radiation whose spectral composition includes the 7723A°, 7948A°, 8668A° or 10470A° lines, will depopulate the $4s'_{oo}$ metastable state. The amount of this radiation absorbed can theoretically be used to determine the population of this metastable state. The increased emission of the 8521A°, 8264A°, 9354A°, 8104A°, 7724A°, 9658A°, or the 9123A° line will also give an indication of the population of this metastable level. Hence, information concerning the concentration of atoms in the $4s'_{oo}$ metastable state may be sought through increased emission of radiation in depopulation or by absorption of energy from a beam of radiation of the correct spectral composition.

It is also evident from Figure 9 that the absorption of radiation composed of the 8115A° line will not depopulate the $4s_{12}$ metastable state. Absorption of this energy will excite atoms to the $4p_{23}$ level, but the only allowed dipole transition is back to the $4s_{12}$ metastable

level. The amount of radiation absorbed at this wavelength can be used to determine the population of this metastable state. Furthermore, Robertson's theory on moving striations, which has metastable atoms as its principal quantity, may be strengthened if data can be gathered which shows that irradiation of an argon glow discharge with the 8115A^{o} line has no effect on the striation parameters. The 8115A^{o} line is an interesting one for study.

The major objectives of this work are to compare the changes in basic striation parameters when the argon discharge is irradiated with illumination from another argon glow discharge and when it is subjected to radiation at 8115A^{o} wavelength, with the striation parameters of the non-irradiated discharge; second, to secure data on the absorption of the 8115A^{o} line to be used in determining the population of the $4s_{12}$ metastable state.

3.2 Intensity Measurements

From the recommendations of Varnadore [27] and Mischke and Schmidt [13], attempts were made to determine what discharge conditions resulted in the most intense emission of the 8115A^{o} line in an argon discharge. This optimum set of conditions would then be used to furnish the source of 8115A^{o} radiation in the major investigations. Two different tube designs were selected for these measurements. Since the source will be operated above the critical current for the elimination of moving striations, measurements were made at currents above 200ma.

To determine the intensity of the 8115A^{o} line, a 7102 photomultiplier tube, with an 8115A^{o} interference filter placed in front of the photocathode, was placed at various positions along the discharge tube. The photo tube signal was sent to a Tektronix 541 oscilloscope which had a 10-K-ohm resistor in parallel with the 1-M-ohm input resistor of the oscilloscope. The intensity was then taken as the difference between the maximum D.C. (including ripple) voltage and the A.C. (peak to peak) voltage as indicated on the oscilloscope. The

sensitivity scale used was 0.05 volts/cm vertical display and 1ms/cm horizontal display.

Discharge tube A was operated hot cathode, with an auxiliary discharge at the anode. Intensity measurements were made at several positions along the tube, measured from the cathode. Gas pressures ranging from 1mm Hg (= 1 torr) to 12.5mm Hg were studied. Currents ranged generally from 200-1800ma. Discharge tube D was operated cold cathode without an auxiliary discharge at the anode. The upper limit on the current was less than with the other tubes. This was required to prevent overheating of the cylindrical electrodes. Measurements were made at two positions on the discharge tube, the first position being 20cm from the cathode, the second being end-on to the discharge tube at the anode end. Two different gas pressures were studied, Using the experience gained from the study of discharge tubes A and D, tube E was filled to .94 mm Hg and later to 13.02mm Hg and operated hot cathode. Measurements were made at positions 10cm and 16cm from the cathode and end-on at the cathode end. The results of these intensity measurements will be presented in section 4.1.

3.3 The Effect of External Radiation on the Basic Striation Parameters and the Discharge Potential

The striation frequency, wavelength amplitude and the discharge potential were determined as functions of current at three different pressures. These measurements were made under three different conditions. First with no external radiation, then with external radiation from another argon glow discharge operated above its critical current for elimination of moving striations, and finally with external radiation from the same discharge as before but with the radiation first passed through an 8115A$^{\circ}$ interference filter. Both the filtered and unfiltered radiation was passed through an optical slit. Attempts to get the intensities of the filtered and unfiltered illumination equal, as determined on the 0.05v/cm scale of the oscilloscope were not successful. A ratio of unfiltered to filtered illumination of three to one was used.

The source in both cases was located at the same distance away from the main discharge. Frequencies were measured with a Hewlett Packard Model 521C, electronic counter. Oscillographs were taken at a few currents as a check on the accuracy of the counter. The changing light intensity of the 8115A° line was sent through the photomultiplier tube to the oscilloscope. A Hewlett Packard decade amplifier was connected in parallel with the oscilloscope input terminal. This signal was amplified by 40 db and used to trigger the oscilloscope. The electronic counter was then connected in parallel with the trigger input. This insured that the vertical signal was of sufficient amplitude to be counted.

Wavelengths were determined by using two movable photomultiplier tubes mounted on tracks, each having a centimeter scale. The photo tubes were placed on opposite sides of the main discharge tube. These tubes were aligned opposite each other so that the signals, as seen on the dual trace oscilloscope, had the same amplitude and were in phase. Both PM #1 and PM #2 had 8115A° interference filters in front of their photocathodes. PM #1 remained fixed and PM #2 was moved away from its original position until the two signals were again in phase. Several positions to the right and left of PM #1 were found in which the two signals were in phase. The distance between the two PM tubes when the signals were again in phase was taken as one wavelength. A photograph showing the PM tube arrangement and some of the other experimental equipment is shown in Figure 10.

The discharge tube potentials were determined as a function of current for three different pressures. A high input-impedance volt meter was used. Measurements were made within the striation regime and above the critical currents for elimination of striations.

The main discharge was irradiated at a position of 10cm from the cathode.

The source was placed normal to the main discharge tube. The resonant wavelength was selected first with an interference filter and later with a Bausch and Lomb Monochromator. I resorted to the mono-

chromator after discovering that I required three interference filters, one for each PM tube and one for the source, but possessed only two. Wavelength measurements and the later absorption experiments required the simultaneous use of both PM tubes with filters. Frequency measurements, and amplitude comparison required the use of only one PM tube with filter. The cathode filament current was maintained at a constant value throughout the series of measurements. The frequencies were measured while steadily increasing the discharge current from the lowest value which gave a stable wave form, to the highest. The use of an auxiliary discharge at the anode did not suppress anode oscillations at all currents of interest, although currents up to 500ma were used. The location of the filaments relative to the cylinder was perhaps incorrect. By using the electronic counter to measure frequencies, several readings could be taken at the same current and a statistical error determined. Five one-second counts were made at each current providing precision of the order of 2% or better. An occasional photograph of the oscilloscope trace was made as a cross check on the electronic counter. The wavelengths were measured in conjunction with the frequency. Four or five measurements were made at each current and a statistical error computed. This provided precision of the order of 0.1 to 0.5cm. Figure 11 is typical of signals from two photomultiplier tubes during wavelength measurements. The results of these experiments are given in section 4.2.

3.4 The Absorption of the 8115A^{o} Line

A photograph showing the arrangement of the source discharge, the main discharge, and the photomultiplier tubes are shown in Figure 12. The irradiating source was placed adjacent to the main discharge tube at a position 10cm from the cathode. The source discharge tube was covered with a light shield. PM #1 was placed in line with the source on the opposite side of the main discharge tube. The source discharge was started and the intensity of the 8115A^{o} line was determined. The beam was collimated by a system of lenses. A beam of

8115A^{o} was then passed through the filled, but not operating, main discharge tube. The 8115A^{o} line was selected with an interference filter. The intensity, I_1 , detected by PM #1 placed adjacent to the main discharge tube directly in line with the beam, was recorded. The source was then extinguished. The main discharge was ignited, and the two photomultiplier signals were sent to a differential amplifier where, after some adjustment, the signals were cancelled. The source discharge was again started and the 8115A^{o} radiation passed through the main glow discharge. With the original signals cancelled, any signal shown on the oscilloscope is $(I_1 - A)$ where A is the amount absorbed by the discharge. Since I_1 is known, A could now be determined. The main discharge was operated with striations present and above the current for elimination of striations. A gas pressure of .81 mm Hg was studied. The source discharge was operated well above the striation current. The photocathodes were cooled to reduce the dark current noise. When the two signals were cancelled, the position of PM #2 was fixed, which completed the initial conditions for the experiment. Photographs were taken of the oscilloscope trace when the cancellation of signals occurred. The source was turned on and a photograph was taken. Finally a photograph was taken showing the intensity, I_1 , of the source. It was believed that by observing a set of several photographs, each set taken at a different current, the intensity absorbed, A, would be determined with a fair degree of accuracy. Observations and results are discussed in section 4.3.

4. Observations and Analysis

4.1 Intensity Measurements

The intensity of the 8115A^{o} line from an argon glow discharge at various currents and pressures was determined. Discharge tubes A, D, and E were used, and the auxiliary discharge at the anode technique was used with tubes A and E. Anode spot oscillations were not suppressed over the entire range of currents of interest with the auxiliary discharge operating at 65ma and 320 volts. This may have been caused by

insufficient current and/or lack of the proper alignment of the anode filament with the end of the cylinder which surrounds it. Tube D was not constructed for use of the auxiliary discharge. The value of the auxiliary discharge for intensity measurements appears to be questionable above the striation critical currents, as the light intensity oscillations appear to be identical in amplitude with and without the auxiliary discharge. (See Figure 13). The same slit width was maintained.

Discharge tube A was operated hot cathode at 1.01mm Hg, 4.97mm Hg and 12.5mm Hg gas pressures, over a current range of 200-1500ma. For this tube configuration, the intensity was found generally to increase with current and with pressure, when measured at the same position along the discharge tube. (See Figure 14). At the low pressures (1.01mm Hg and 4.97mm Hg) the intensity was greater at a position nearer the cathode. Measurements were made at positions 10, 15, 20, 25, and 30 centimeters from the cathode for the gas pressure of 1.01mm Hg; at positions 10, 15, 20 centimeters from the cathode for the gas pressure of 4.97mm Hg; at positions 10 and 15 centimeters from the cathode for the gas pressure of 8.05mm Hg, and only at a position 20 centimeters from the cathode for the gas pressure of 12.5mm Hg. Figure 15 shows the intensity as a function of current at various distances from the cathode. Measurements are considered to be accurate within 5%. At least three different measurements were made at each current.

While working with the discharge at 1.01mm Hg, it was noted that the current required to eliminate striations increased with distance from the cathode. This is in excellent agreement with the results of Cooper and Oleson [10], that there is no unique critical current at which striations simultaneously disappear from the entire positive column but disappear progressively from the cathode end. Figure 16 shows the critical current for disappearance of moving striations as a function of distance from the cathode.

Discharge tube D was operated cold cathode at 1.81 and 6.18mm Hg.

The current range was 10-300 ma. Measurements were made at positions 20.5cm from the cathode and end-on to the discharge tube at the anode. Striations were present in the positive column at this maximum current setting. The limited current was due to the severe heating of the cylindrical electrodes and its corresponding outgassing problem. The measurements here are considered to be slightly inaccurate due to the sometimes severe instability of the positive column. The measurements generally showed that intensities end-on to the discharge tube were greater than those at the position 20.5cm from the cathode. These results are summarized in Figure 17.

Discharge tube E was operated with and without an auxiliary discharge at the anode. The auxiliary discharge had no effect on the intensity. It only enabled one to obtain stable wave forms over most of the currents for striations. Since the source discharge will be operated above the striation critical current, its usefulness is doubtful. Intensity measurements were made at positions 10, and 16 cm from the side arm containing the cathode and end-on at the cathode end. Gas pressures of 0.94mm Hg and 13.02mm Hg were studied. The intensity again was found to increase with increasing current, and pressure. The intensity end-on at the cathode end was greater than that found at positions along the discharge tube. This increase in intensity near the cathode may be due to the continuous spectrum from the tungsten filament used as the cathode. Although the glowing tungsten filament was placed in a side arm and the optical slit to the photomultiplier was shielded from its direct radiation, there was still reflection from the walls of the discharge tube. The contribution from reflection is believed to have been very minor however. The negative glow was also in the side arm, thereby insuring that the end-on position of the photomultiplier received the illumination of the positive column. The increase in intensity when measured end-on rather than side-on is probably due to the discharge being optically thin. The increase in intensity measured at positions near the cathode may be explained in the following

manner. If the population of metastable atoms is greater near the cathode, then there might be more dipole transitions per unit time in this area. If the increased transitions are between the $4P_{23}$ excited state and the $4s_{12}$ metastable state, then there would be an increase in the emission of 8115A^{o} radiation. The work of Mischke and Schmidt [13], who found that the discharge potential showed the greatest increase when the discharge is irradiated near the cathode, together with the work of Meissner and Miller [11], who related their observed discharge potential increase to transitions involving metastable atoms, may be used to support the position that there are more transitions involving the metastables near the cathode.

Two other advantages gained by measuring the intensity end-on at the cathode end are: (a) with the cathode in a side arm the photomultiplier does not receive the direct radiation of the glowing cathode as it would if it were placed end-on at the anode end, or if the cathode were not in a side arm, (b) the current required to eliminate the striations is much less at the cathode end.

In summary it was observed that: (a) the current required to eliminate moving striations increased with increase in distance from the cathode, (b) a discharge tube similar to tube E gives the greatest relative intensity of the 8115A^{o} line, if measurements are made at the cathode end and the photocathode is shielded from the direct radiation of the glowing cathode, (c) the increased intensity noted when measurements were made end-on at the anode had a large contribution from the continuous spectrum of thermal radiation from the glowing cathode even when the filter or monochrometer is set at the desired wavelength, and finally (d) the intensity of the 8115A^{o} line increases with an increase in current and pressure, at least over the range investigated. The upper limit on the current, in practice, is determined by the capacity of the power supply used, and the severe heating of electrodes at high currents. It was decided that discharge tube E, hereafter called the source, would be filled with argon to about 9mm Hg and operated

hot cathode without the auxiliary discharge at a discharge current of 1400ma.

4.2 Effects of External Illumination

A comparison of the striation parameters during irradiation of the main discharge with the striations parameters with no external radiation, is presented here.

Prior to the experiments conducted with the main discharge tube, tube A, some preliminary experiments were made to determine the wave length, frequency and velocity as functions of discharge current and gas pressure, with no external radiation. The auxiliary discharge was not used in these measurements. In general, striation frequencies decreased rapidly with increasing current at low currents (20-150ma), became rather constant over the range 200-700ma, then increased with current, as the critical current was approached. (See Figure 18) These observations are in general agreement with those reported by Cooper [6]. The variation of frequency with pressure was found to be irregular.

Wavelengths were found to be inversely proportional to the pressure, and at low pressures a continuous function of current. These results are shown in Figure 19 and Figure 20 respectively. Neither the proportionality of wave length to the tube radius, R^n, where n varies between 1.5 and 2, as reported by Kenjo and Hatta [15], nor the wave length being 2 or 3 times the tube diameter as reported by Alexeff and Jones [16], were noted in these experiments. The wave length varied from nearly equal to the tube diameter at high pressures to nearly 4 times the diameter at low pressures.

The velocity of the striations was calculated from the product of the frequency and wavelength at each pressure and current where both were measured. The velocity generally decreased with increasing pressure and current. These observations are all in general agreement with those of other investigators.

To study the effects of external radiation on striation parameters,

a high gain differential amplifier with a sensitivity range of 1 mv to 50 volts was used. Both photomultiplier tubes were cooled with dry ice (-44°C) to eliminate practically all of the dark current noise. Dark current noise was reduced to less than one millivolt.

Although a desire to determine the effect of external radiation on moving striations as a function of source position measured from the cathode existed, time would not permit such a detailed study. The source was placed 10 cm from the cathode and remained in this position throughout the measurements. Attempts to keep the intensity of the unfiltered source equal to the filtered (8115A°) source were not successful. The intensity of the unfiltered illumination was so much greater than the intensity of the 8115A° line, that all attempts to equate the two were unsuccessful. The procedure used to attempt to get equal intensities involved the following: First the source illumination was passed through an optical slit in front of a photomultiplier and the dc signal on the oscilloscope was noted, then an interference filter was put in front of the photomultiplier and the slit width increased until the same dc signal was seen on the oscilloscope. The maximum slit width permitted an intensity ratio of about three to one. Using this intensity ratio the experiments were performed.

A comparison of the effects of radiation from the entire argon spectrum on striation parameters to those resulting from irradiating with 8115A° radiation cannot be made since their intensities were not equal. For gas pressures of 0.58mm Hg, 4.92mm Hg and 8.27mm Hg, a slight increase (1.5-2%) in striation frequency was observed when the discharge was irradiated with the entire argon spectrum. Due to the precision of measurement, the significance of the small increase is questionable. At some currents, the positive column displayed very irregular oscillations when radiation from the entire argon spectrum was used, but showed regular striations when the external irradiation was turned off. Figure 21 shows the frequency as a function of current.

The effect of the 8115A° line on the striation wave length is shown

in Figure 22. The 8115A^{o} line caused essentially no change in the wave length at the same pressures and currents that the frequencies were measured. Due to the sometimes severe oscillation of the positive column caused by unfiltered illumination it was not possible to measure wavelengths at each of the currents desired. However at those currents where a stable positive column was obtained, the wavelengths with unfiltered illumination did not differ appreciably from those of the non-irradiated or the radiated with 8115A^{o} striations.

The velocity of the moving striations increased slightly when the main discharge was irradiated with unfiltered illumination. This slight increase was due to the increase in frequency, since the wave length remained essentially unchanged. There was no increase in the striation velocity when 8115A^{o} was incident on the discharge tube.

Attempts to detect a change in the amplitude of the striations under the conditions of external radiation were unsuccessful. The striation amplitudes were larger at low pressure than at high pressures. Amplitudes also seem to increase to a maximum value at about one half the striation critical current then decrease to zero when the striations disappeared. No increase or decrease in striation amplitude was noted at any of the pressures and currents studied.

4.3 Results of Absorption Measurements

The technique of determining the amount of 8115A^{o} radiation absorbed by an argon glow discharge by measuring the difference between two oscilloscope traces from photographs lacks the high degree of precision and accuracy required for exacting studies of this nature. However, this technique did give indications of trends which might be related to metastable populations. It was observed that there is a tendency for greater absorption at low discharge currents (30-70ma), than at high discharge currents (200-1900ma). At low discharge currents, the incident beam of 8115A^{o} radiation seemed to increase the amplitude of the small wave form which remained after the two signals from PM #1 and PM #2 were cancelled by the differential

amplifier. This did not occur at currents above the striation critical current. The signals were not completely cancelled by the differential amplifier. The difference in the response of the photomultiplier tubes is believed to have been the major contributing factor. The amplitudes and phases were made equal, visually, yet complete cancellation was not obtained. Figure 23 shows the results of absorption of a beam of 8115A° radiation by an argon discharge.

The tendency for greater absorption at low discharge currents than at high discharge currents may be explained in the following manner. Assuming that Robertson's condition for striations, which depends on metastable concentrations as shown by the term, $-M \frac{dF_3(N)}{dN}$, is true, then by decreasing the metastable populations a decrease in the amplitude of the striations should also occur. This work and the works of Cooper [6, 10] have shown that at high currents the striation amplitude approaches zero. If this condition corresponds to the minimum density of metastable atoms, in particular the $4s_{12}$ metastables, then there should be minimum absorption of 8115A° radiation due to this minimum in density. Conversely at low discharge currents the positive column is well within the striation regime. If this corresponds to a high density of $4s_{12}$ metastables, then there should be greater absorption of 8115A° radiation. The results of this limited experiment tend to substantiate striation dependence on metastables, through the absorption of 8115A° radiation.

5. Conclusions and Acknowledgements

5.1 Conclusions

The relative intensity of 8115A° radiation emitted by an argon glow discharge is an increasing function of current and pressure over the range 20-1500 ma and 0.5-13.0mm Hg, and also a function of distance from the cathode. The relative intensity appeared to be maximized when measured from a position end-on at the cathode end in a discharge tube where the cathode has been placed in a side arm, transverse to the longitudinal axis of the discharge tube. Increase in intensity of

the 8115A^{o} line indicates a denser population of the $4s_{12}$ metastable atoms near the cathode.

External irradiation of one discharge by the illumination from another having the same spectral composition (the source) requires the use of a system of lenses for focusing and collimating the beam to decrease energy loss from the beam. A very intense source is required to cause any appreciable change in the wave length and amplitude of the moving striations or the discharge tube potential. The striation frequency appears to be more sensitive to external illumination, since a slight increase was observed when the ratio of the intensity of the source to that from the main discharge tube is of the order of 10 to 1. These slight increases may be significant since they might be related to depopulation of metastable states as postulated by Mischke and Schmidt [13], Pekarek [12] and others. Since the frequency of moving striations increases as the critical currents for their elimination is approached, the strong emphasis placed on metastable atoms for the initiation of moving striations by Robertson [23] appears to be justified.

The absorption of 8115A^{o} radiation by the argon glow discharge not only can give information concerning the population of metastables in the discharge, it can give information as to the metastable density as a function of distance from the electrodes and as a function of discharge current and pressure. From the present work, it is concluded that absorption studies of single wavelength radiation can lead to a greater understanding of the role of metastable atoms in the initiation of moving striations. The results of this work indicate that striations are present when the density of the $4s_{12}$ metastables is high and are absent when this density is low.

5.2 Recommendation for Further Work

It is recommended that further absorption studies be conducted. A refinement of the technique used in this work may give better results. The technique used here involved visually (with a comparator micrometer)

taking the difference between two small numbers. This may be done electronically by using three 7102 photomultiplier tubes, four interference filters and two oscilloscopes with differential amplifiers. The four interference filters would be used as follows: One for each of three photomultiplier tubes and one to select the radiation to be used. Two of the photomultiplier tubes would be used in the same manner as in this work. The first differential amplifier would then give a signal corresponding to the source intensity, I_1 , minus the absorbed intensity, a. This signal would then be sent to the second differential amplifer. The third photomultiplier would be used to sense the intesntiy, I_1 , and send this signal to the second differential amplifier. By insuring that the intensity, I_1 , as sensed by PM #1 and PM #3 were equal prior to irradiation, these two signals would be cancelled at the second differential amplifier and the oscilloscope trace will be a measure of the intensity absorbed, a.

In addition to the absorption studies, and in view of the limited range of currents and pressures investigated, it is recommended that further work be done in determining the effects of external illumination on basic striation parameters.

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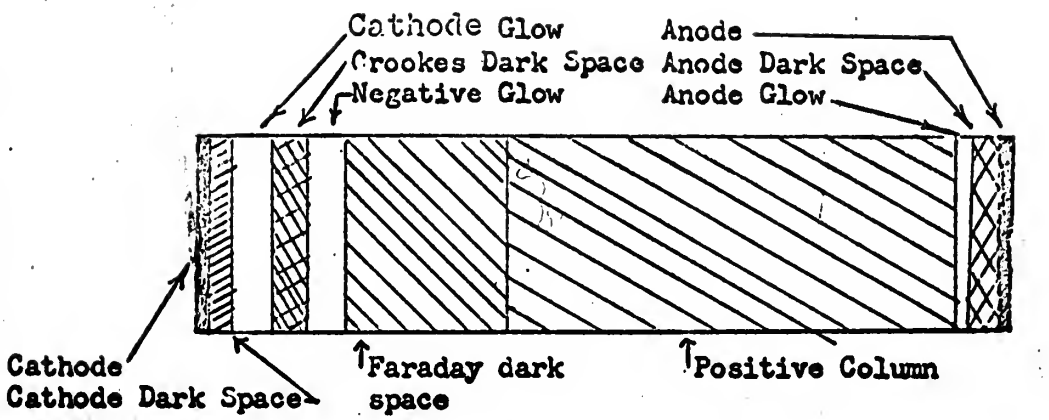
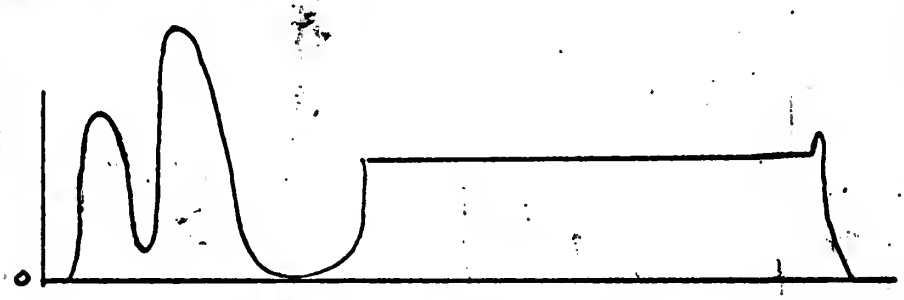
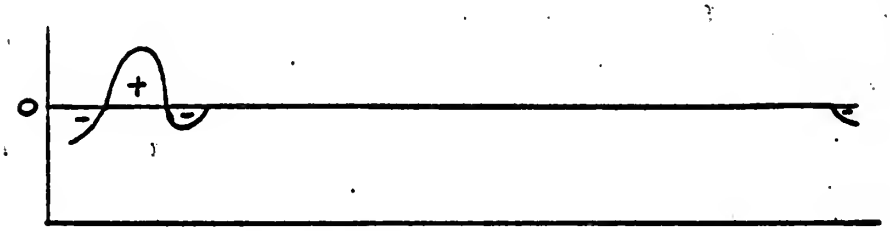




Light Intensity Plot



Charge Density Plot

Figure 1. Regions of a Glow Discharge

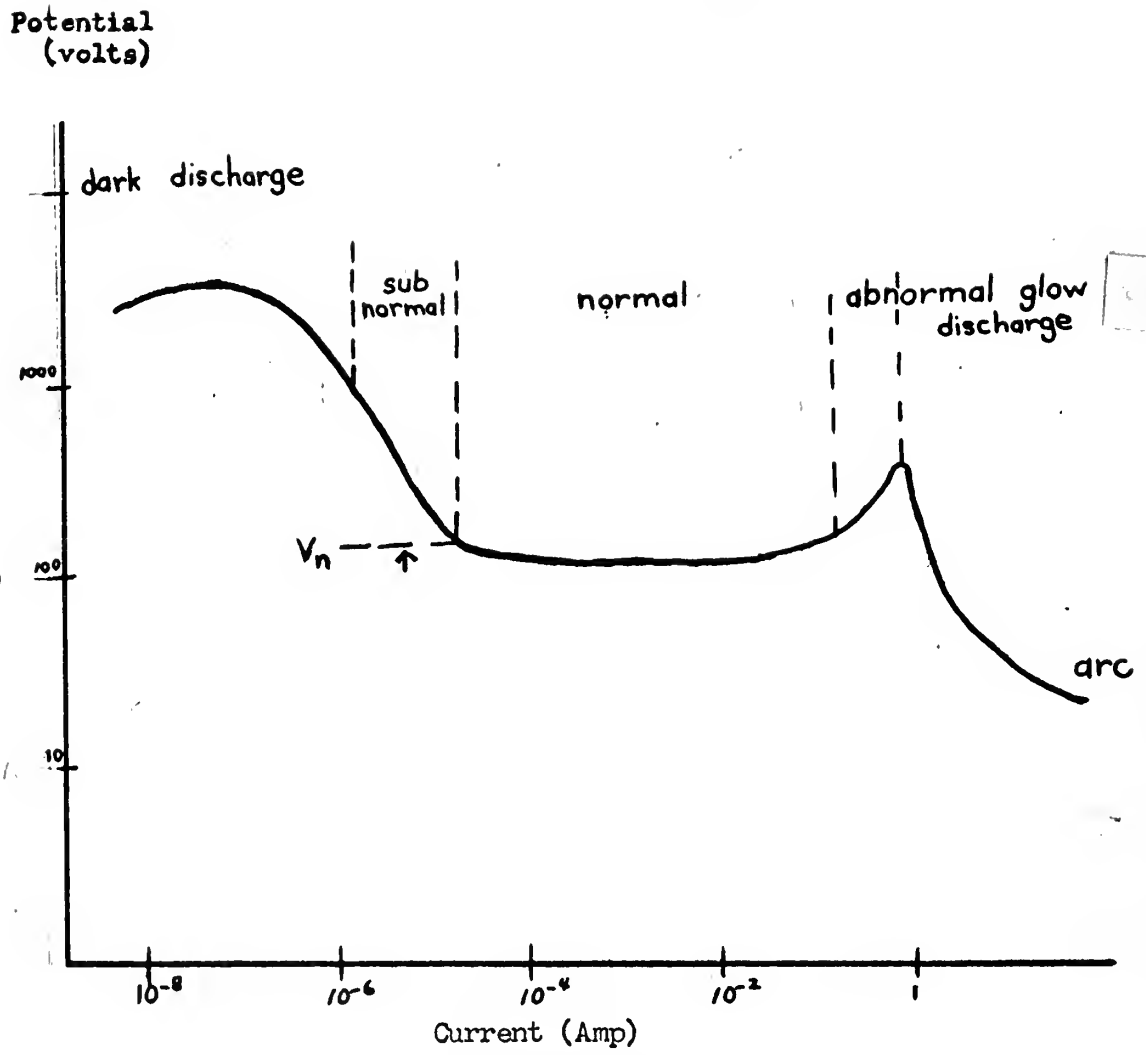


Figure 2. Maintenance Potentials vs Current for a Typical Glow Discharge.

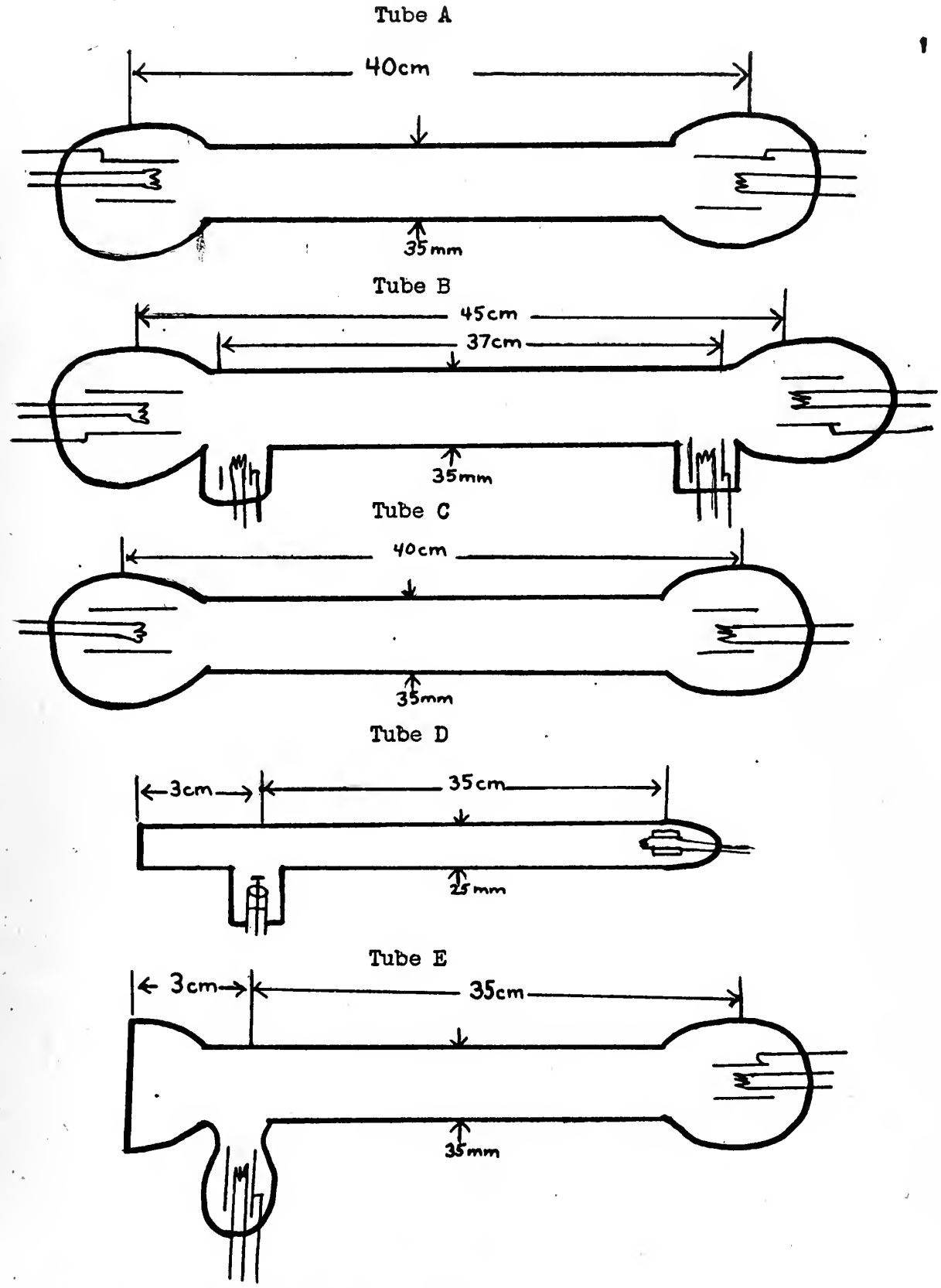
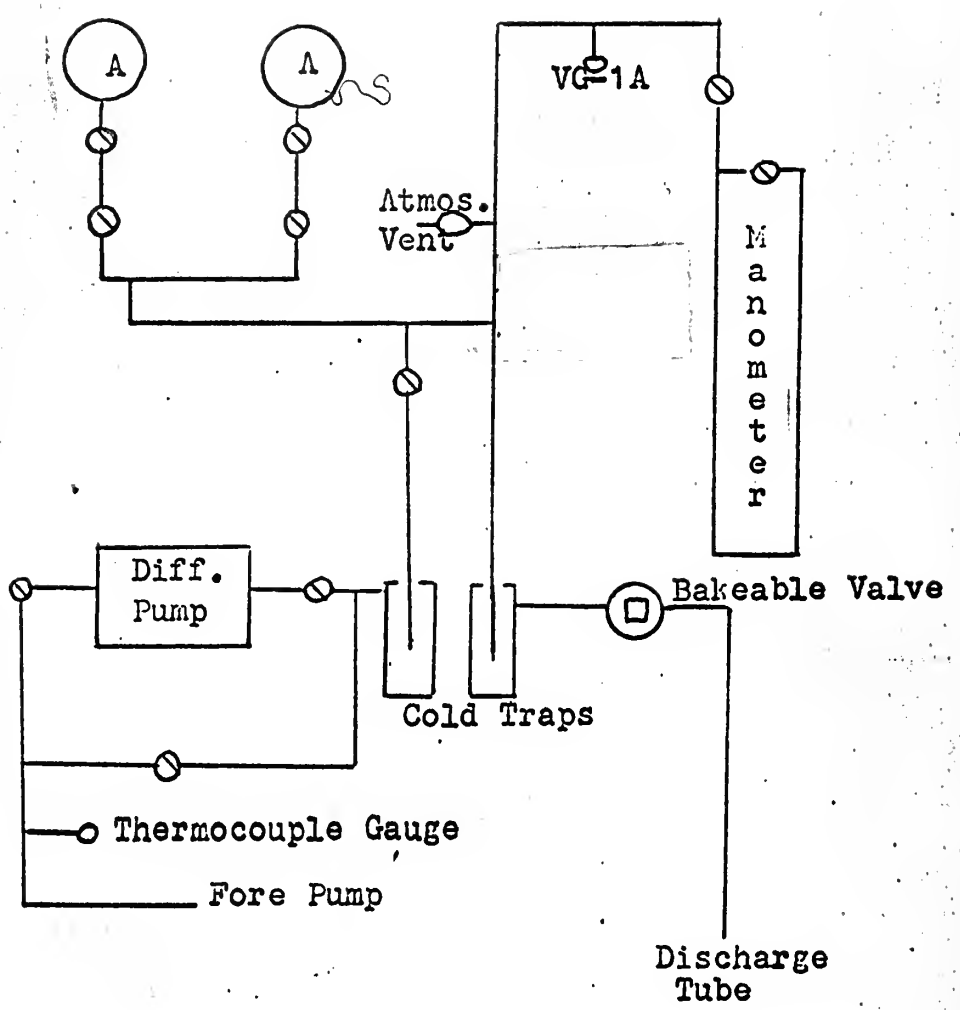
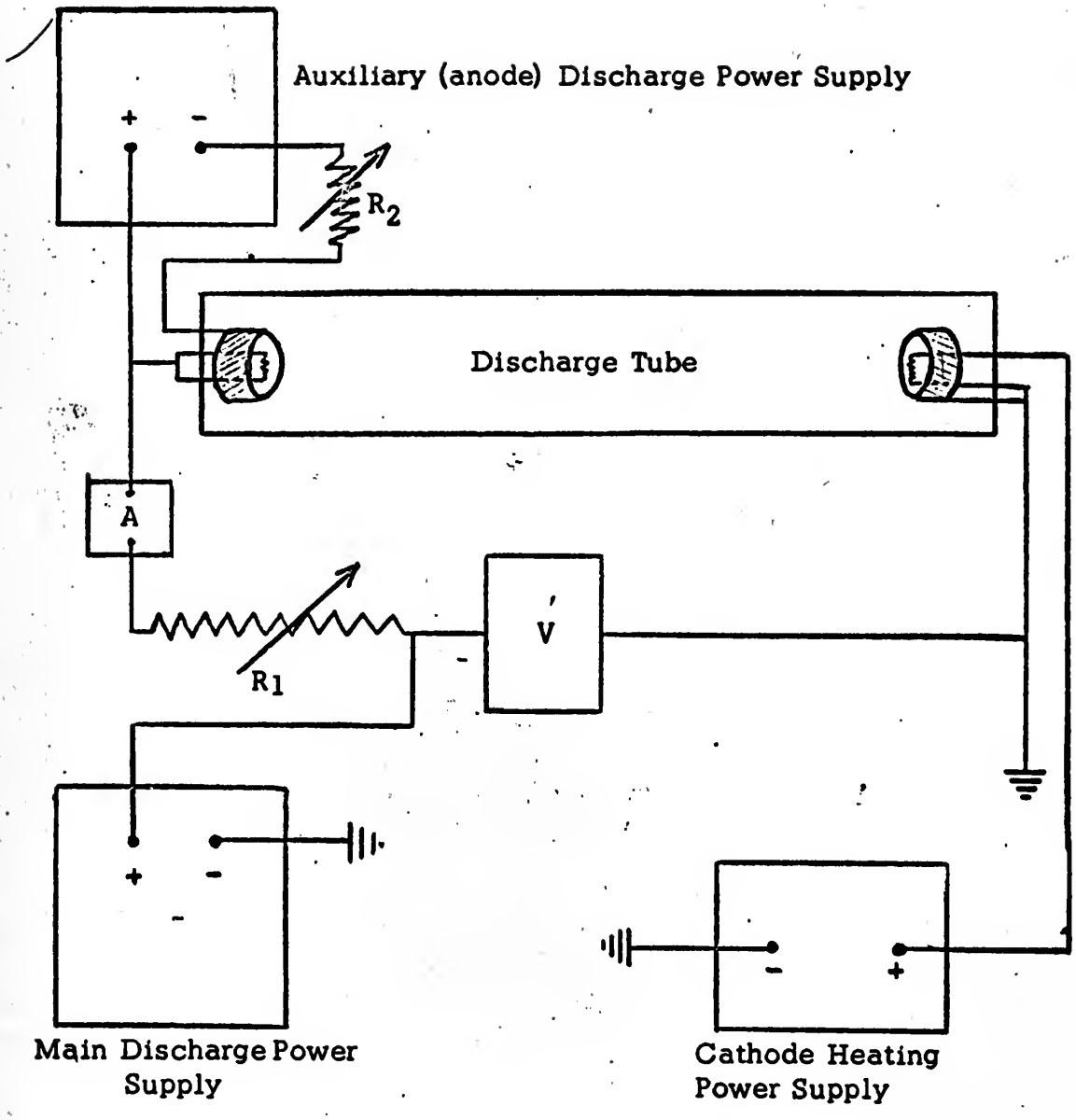


Figure 3. Discharge Tube Design.



The Vacuum System

Figure 4



R_1 Ballast Resistance
R_2 Auxiliary Resistance
A Ammeter
V Voltmeter

Figure 5
Schematic Diagram of Electrical Circuit

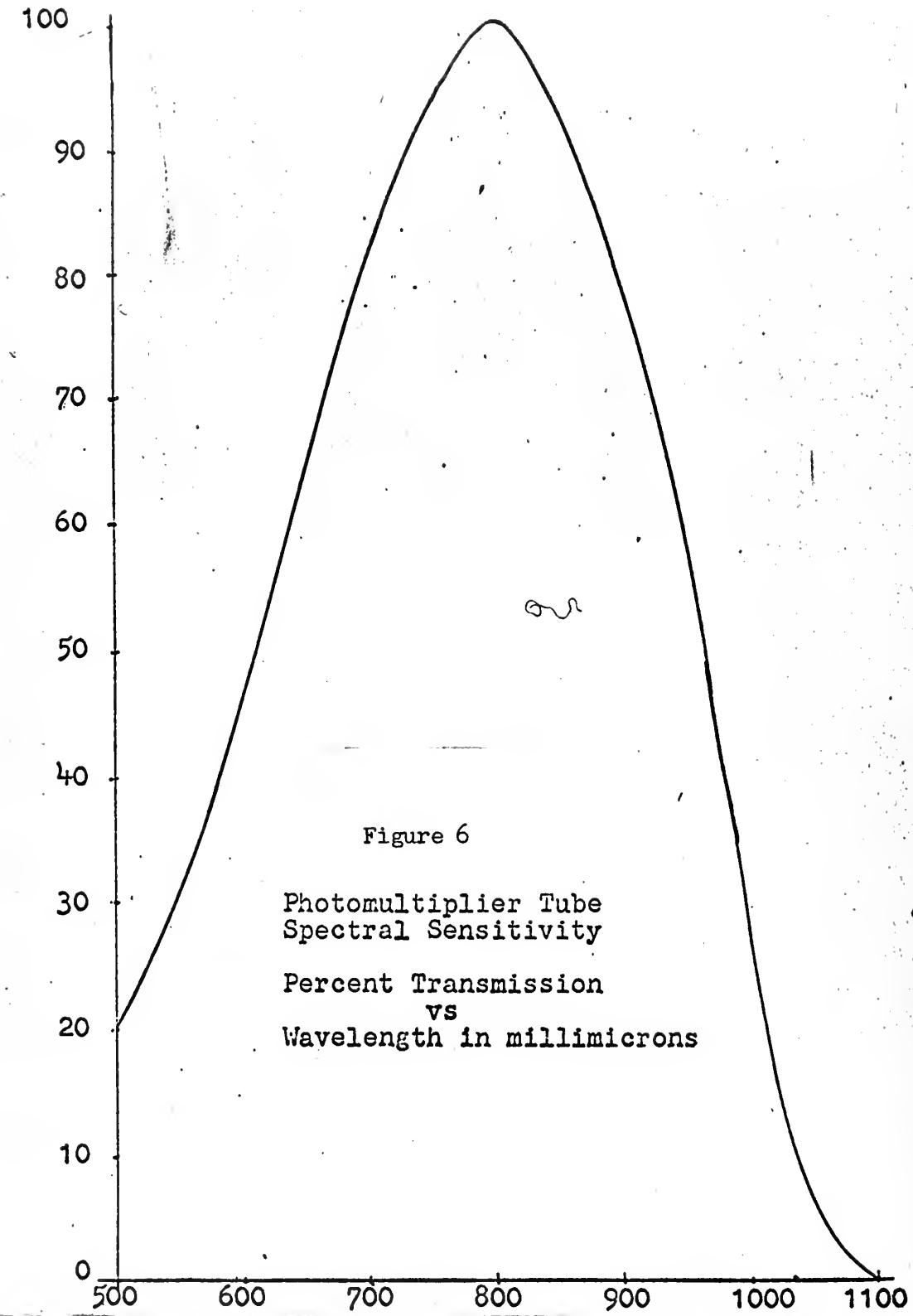


Figure 6

Photomultiplier Tube
Spectral Sensitivity

Percent Transmission
vs
Wavelength in millimicrons

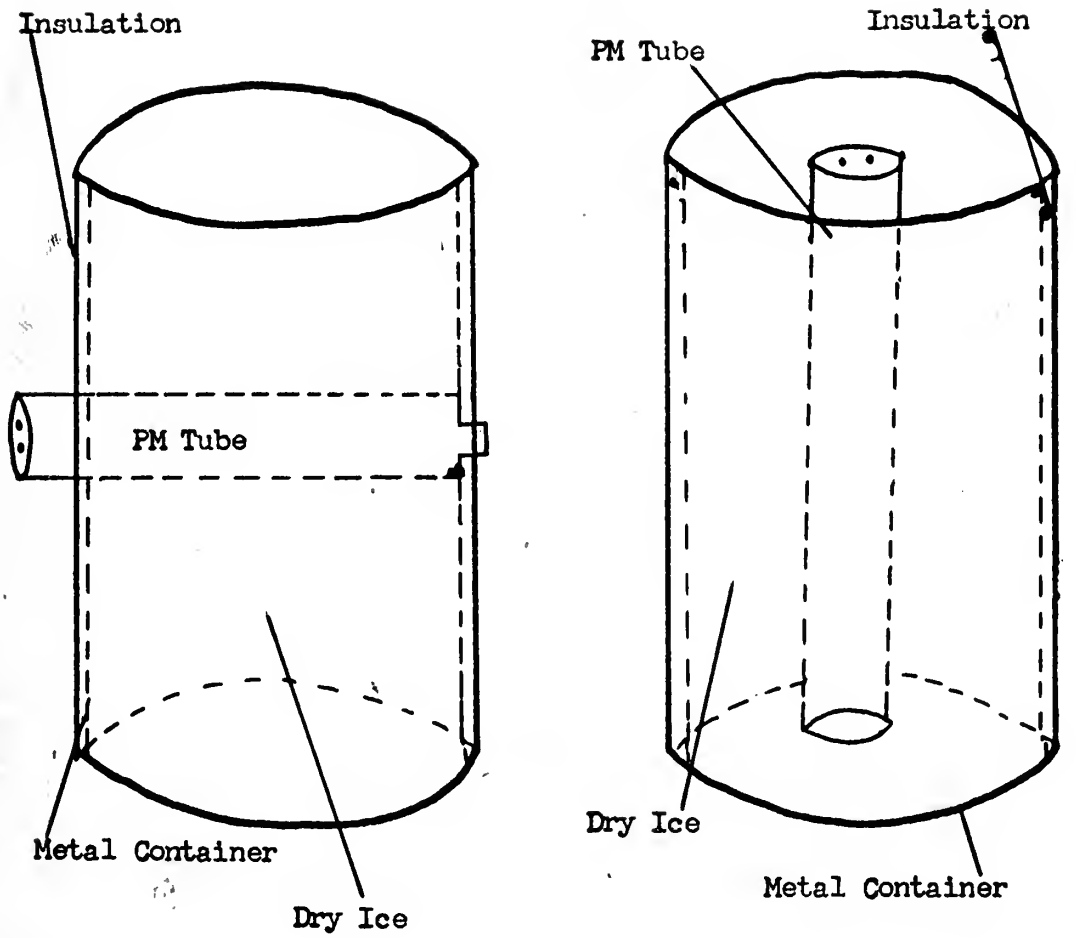


Figure 7. Photomultiplier Tube Refrigerator.

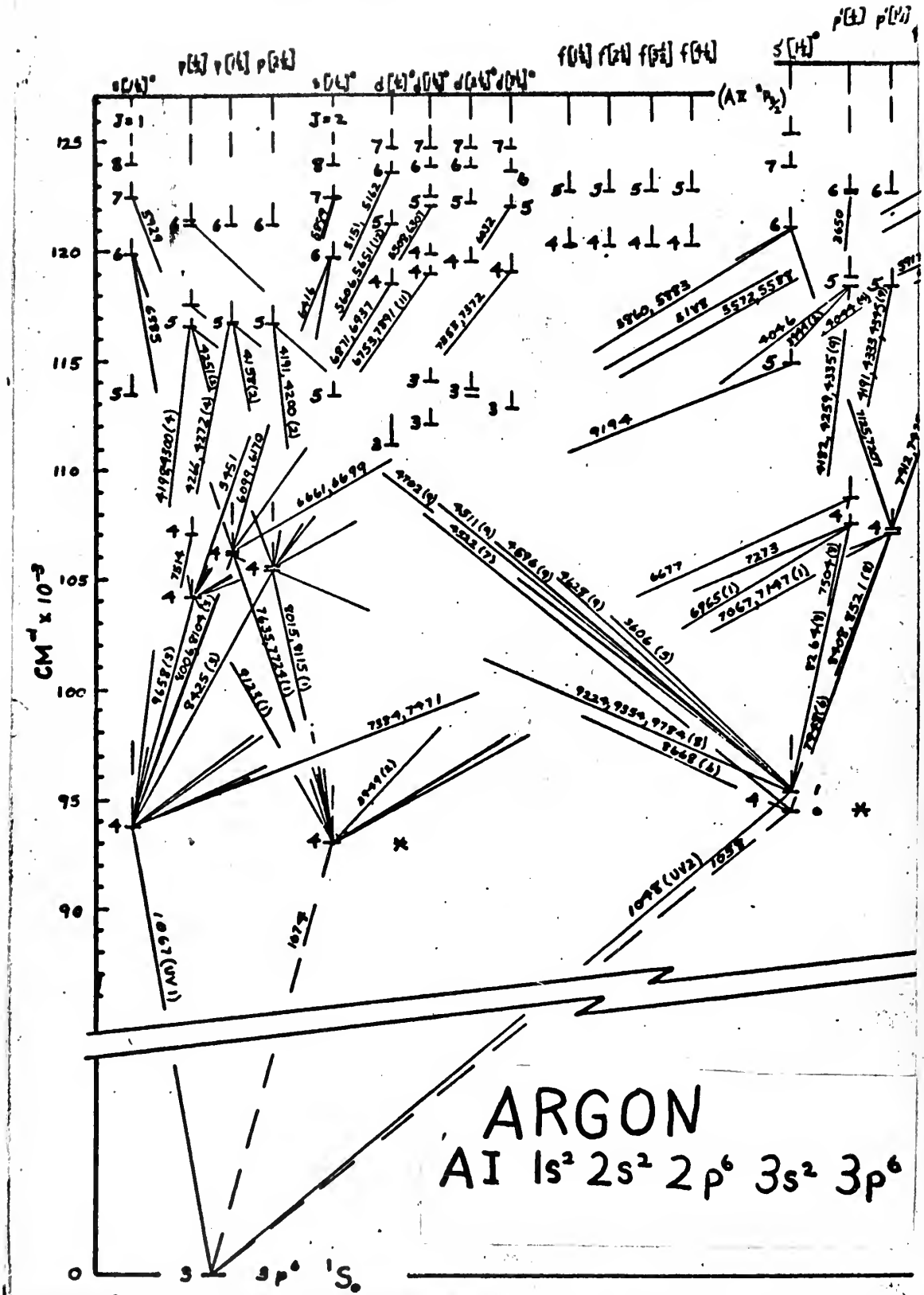
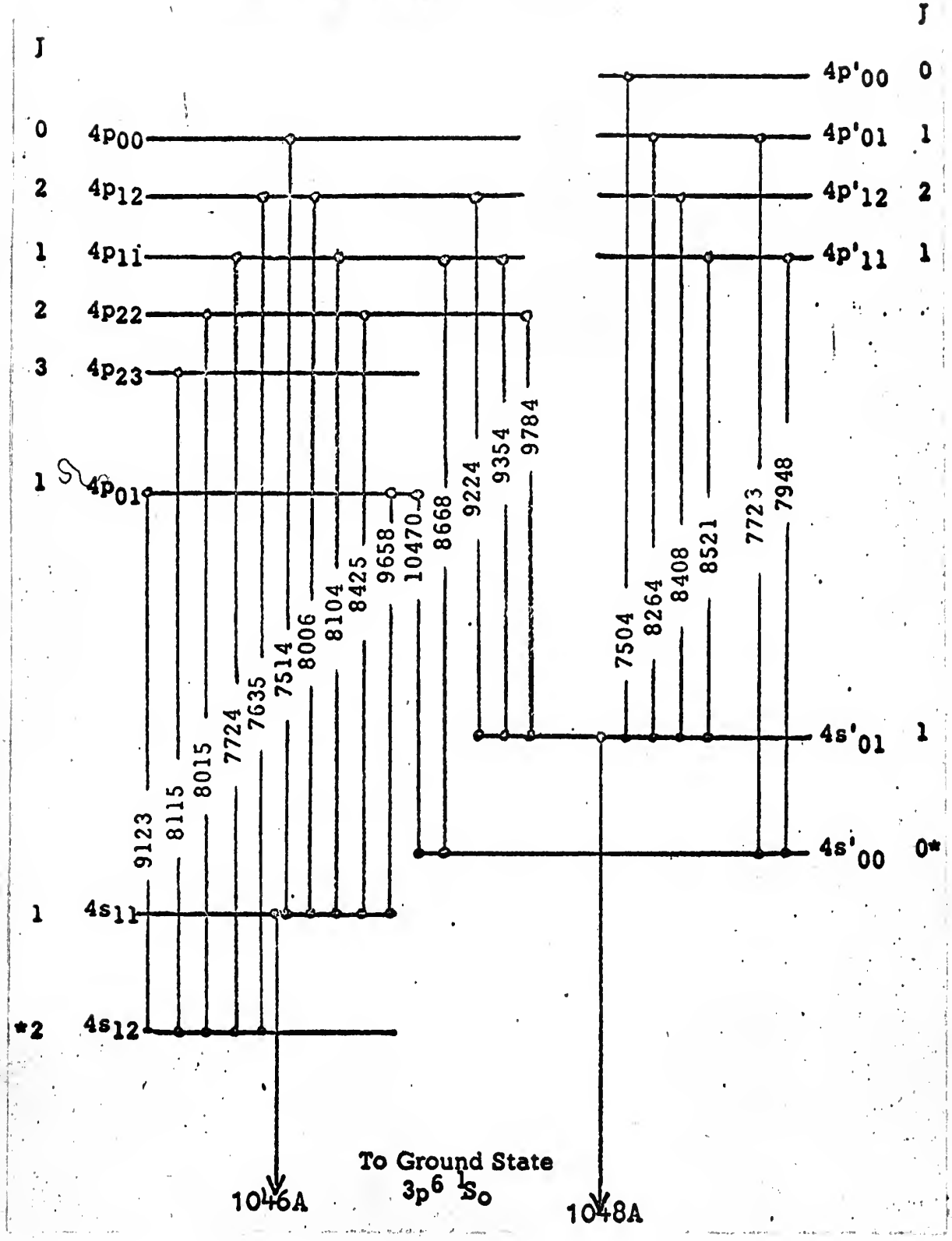


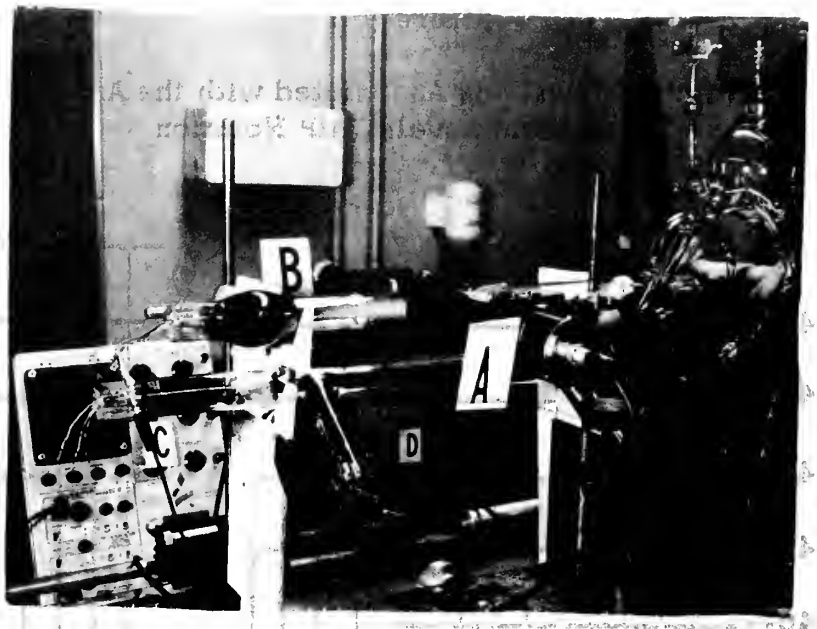
Figure 8. Argon I Grotrian Diagram.

Raymond L. Kelly, U.S. Naval Postgraduate

Figure 9 .

Optical Transitions Associated with the Argon I
Metastable Levels. AIP Notation





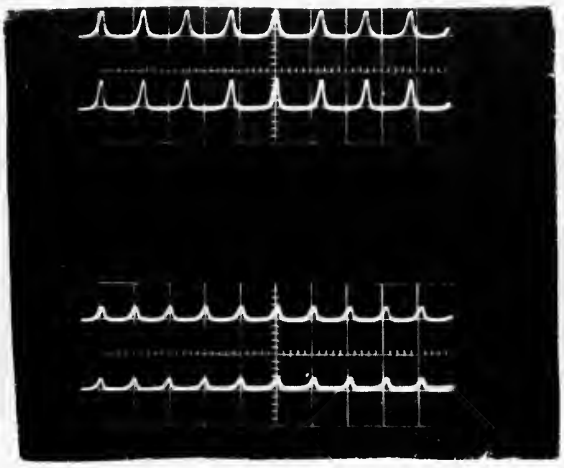
A - [illegible] (Re[illegible])

B - [illegible] (Nov [illegible])

C - Tektronic Oscilloscope, Type 5[illegible]

D - Hewlett Packard Electronic Counter

Figure 10 [illegible] multiplier Tube [illegible] for [illegible]velenate, Frequency and [illegible] Measurement

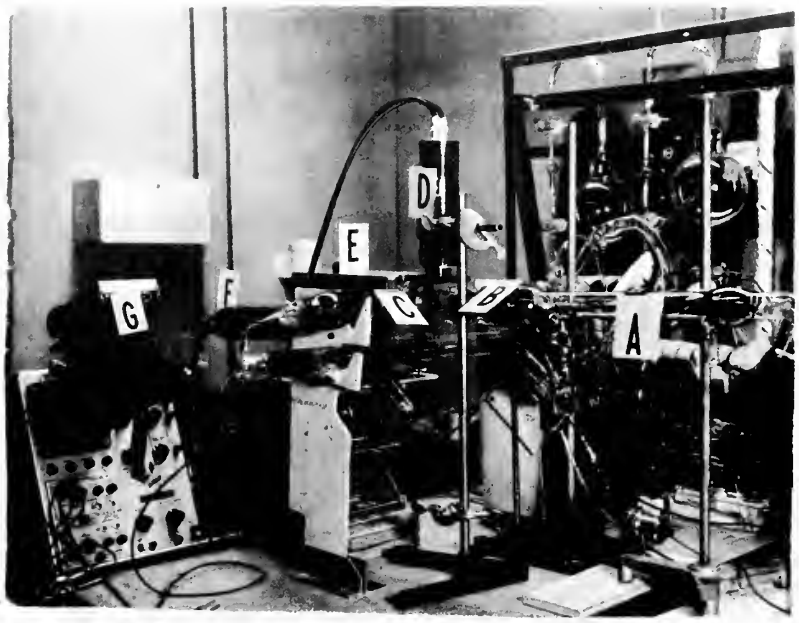


(a)

(b)

Gas Pressure-1.62 mm Hg

Traces (a) Discharge current of 100 ma.
Traces (b) Discharge current of 30 ma.
Vertical sensitivity - v/cm.
Horizontal sensitivity - ms/cm.



A-Source Discharge Tube

B-Lenses For Collimating Beam

C-Main Discharge Tube

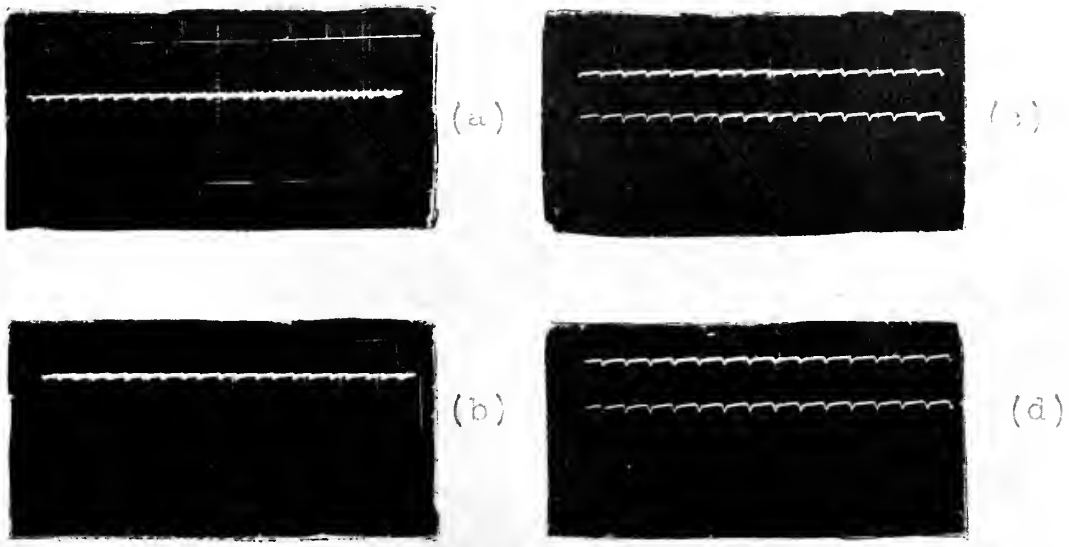
D-PM#2 with 8115A° Interference Filter Attached

E-Bausch & Lomb Monochromator

F-PM#1, Attached to Monochromator

G-Dumont Oscilloscope Attached to Tektronic Oscilloscope, Type [illegible]

Figure 2 [illegible] Arranged [illegible] Absorption [illegible]



(a)A. C. signal with auxiliary anode discharge.
Pressure-4.92 mm Hg.
Discharge current-1100ma.

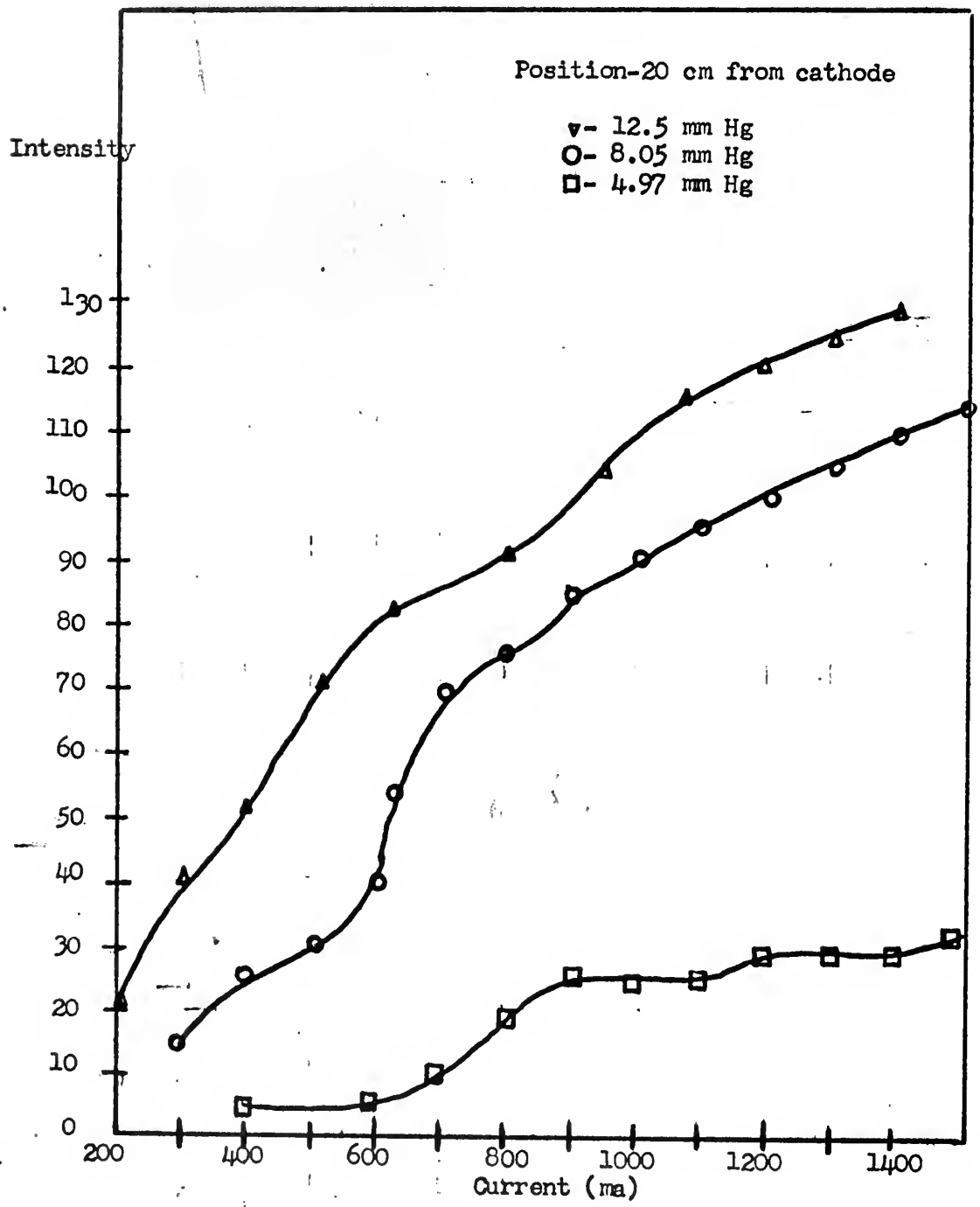
(b)D. C. signal without auxiliary anode discharge.
Pressure-4.92 mm Hg.
Discharge current-1100 ma.

(c)Two D. C. signals in phase with auxiliary anode discharge. Pressure-1.61 mm Hg.
Discharge current-1500 ma.

(d)Two D. C. signals in phase without auxiliary anode discharge.
Pressure-1.61 mm Hg.
Discharge current-1500 ma.

Figure 13 Oscilloscope Photograph of Discharge Light Intensity

Figure 14. Intensity vs Current



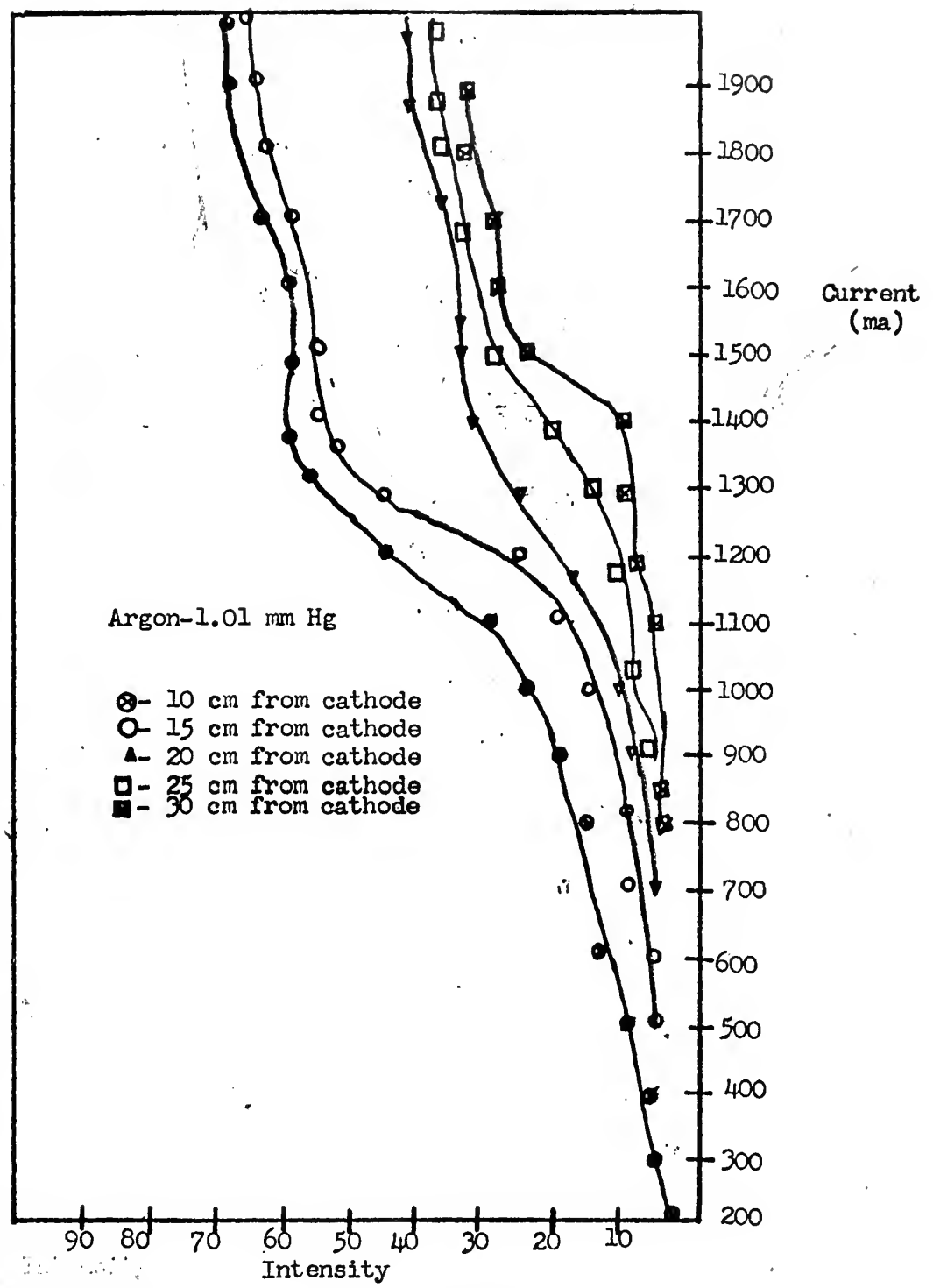


Figure 15. Intensity vs Current For Different Positions From The Cathode.

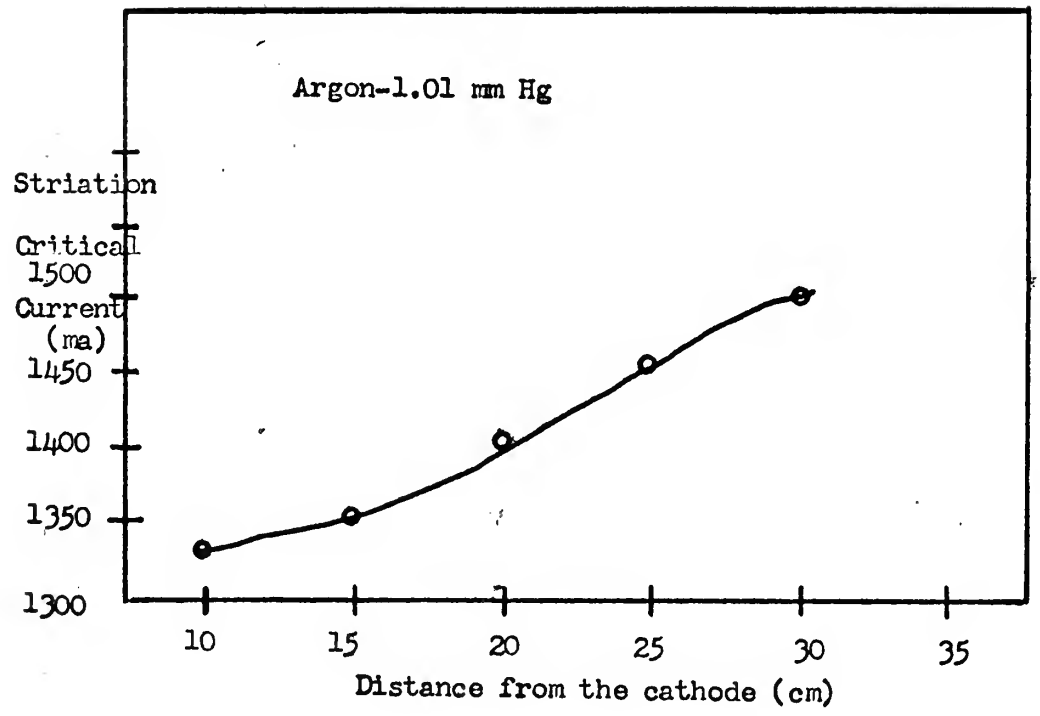


Figure 16. Plot of Striation Critical Current vs Distance From Cathode

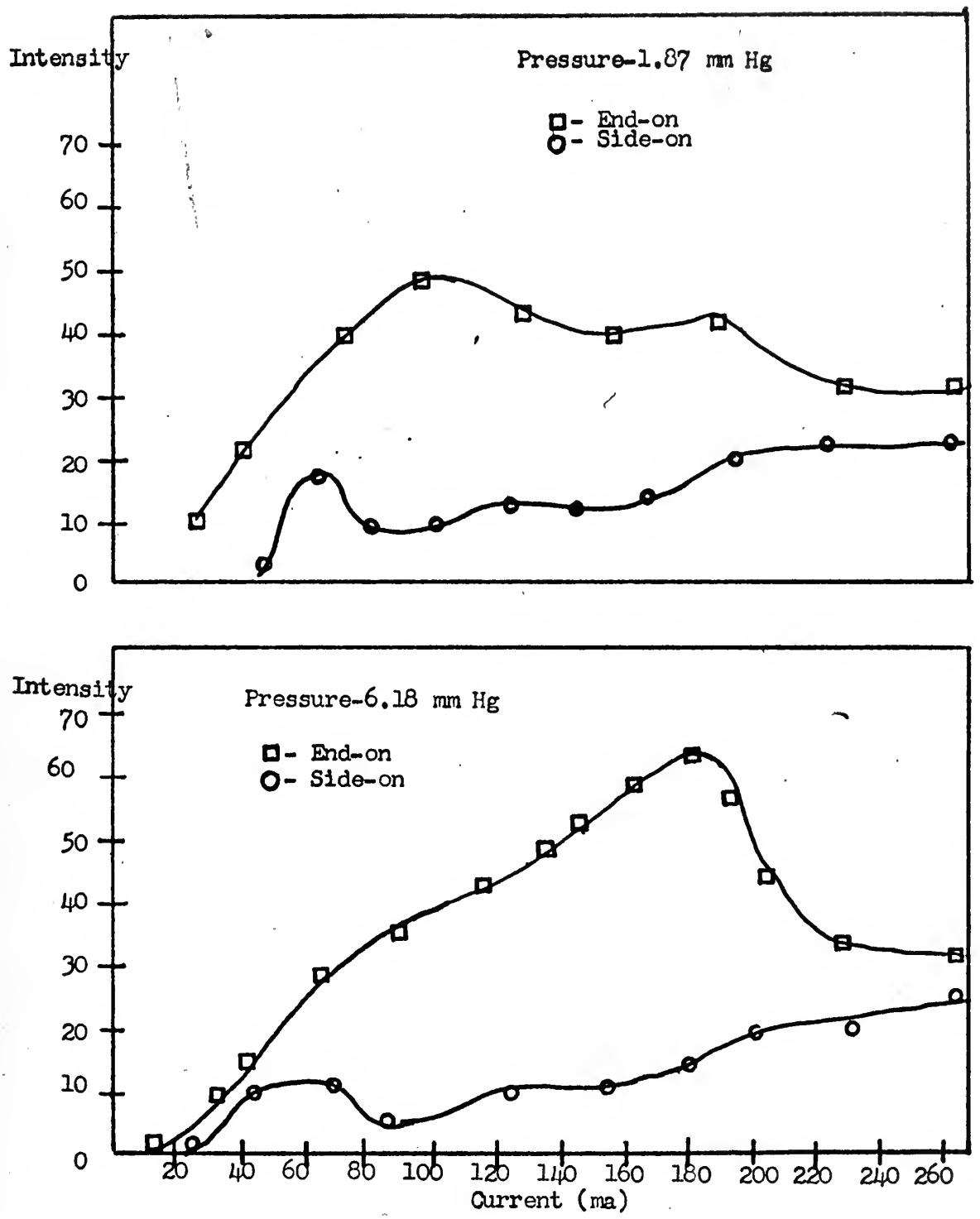


Figure 17. Comparison of Intensity Side-on with Intensity End-on at the Anode. Tube radius-21 mm.

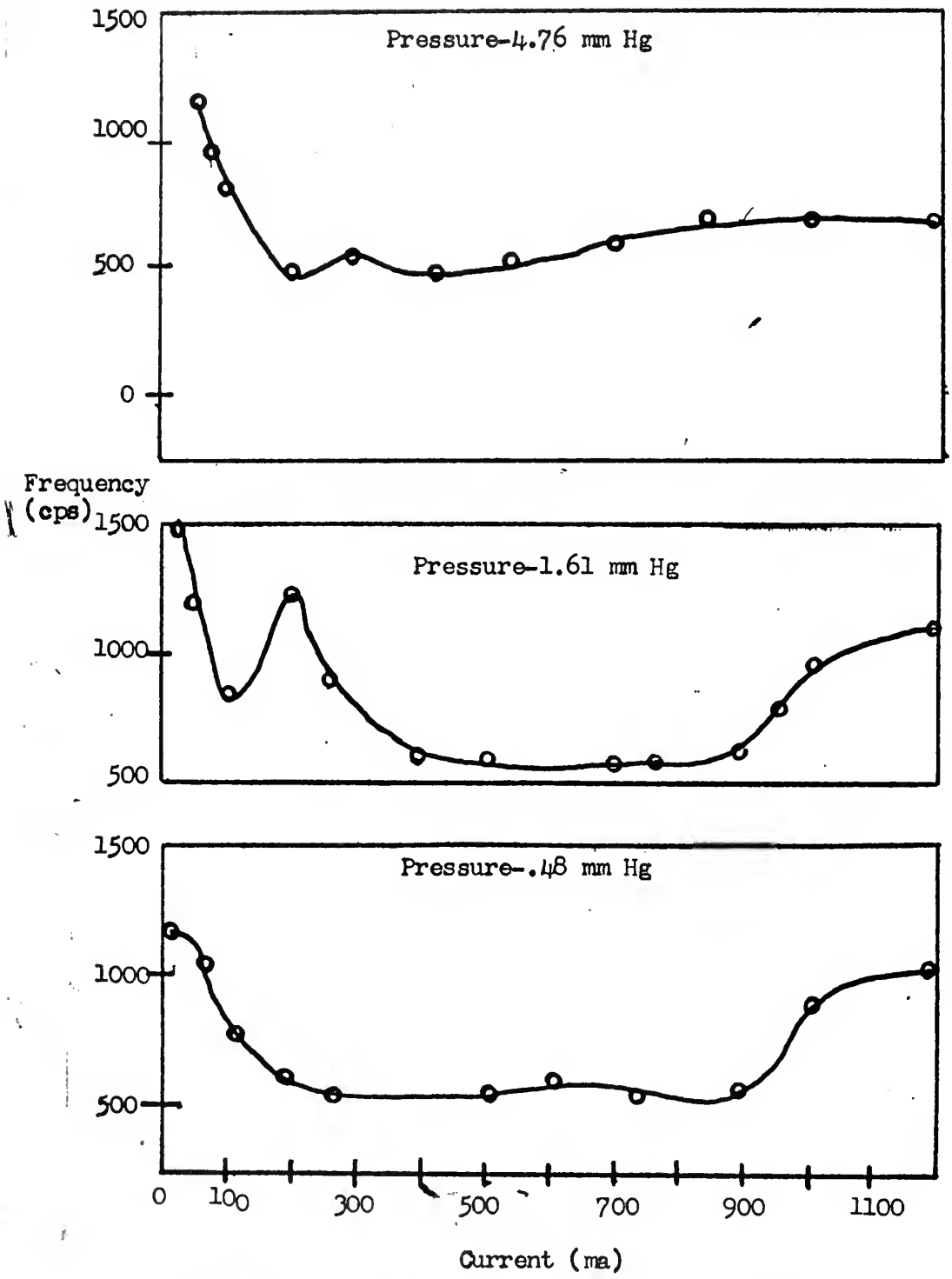


Figure 18. Plot of Frequency vs Current. Tube Radius 31 mm

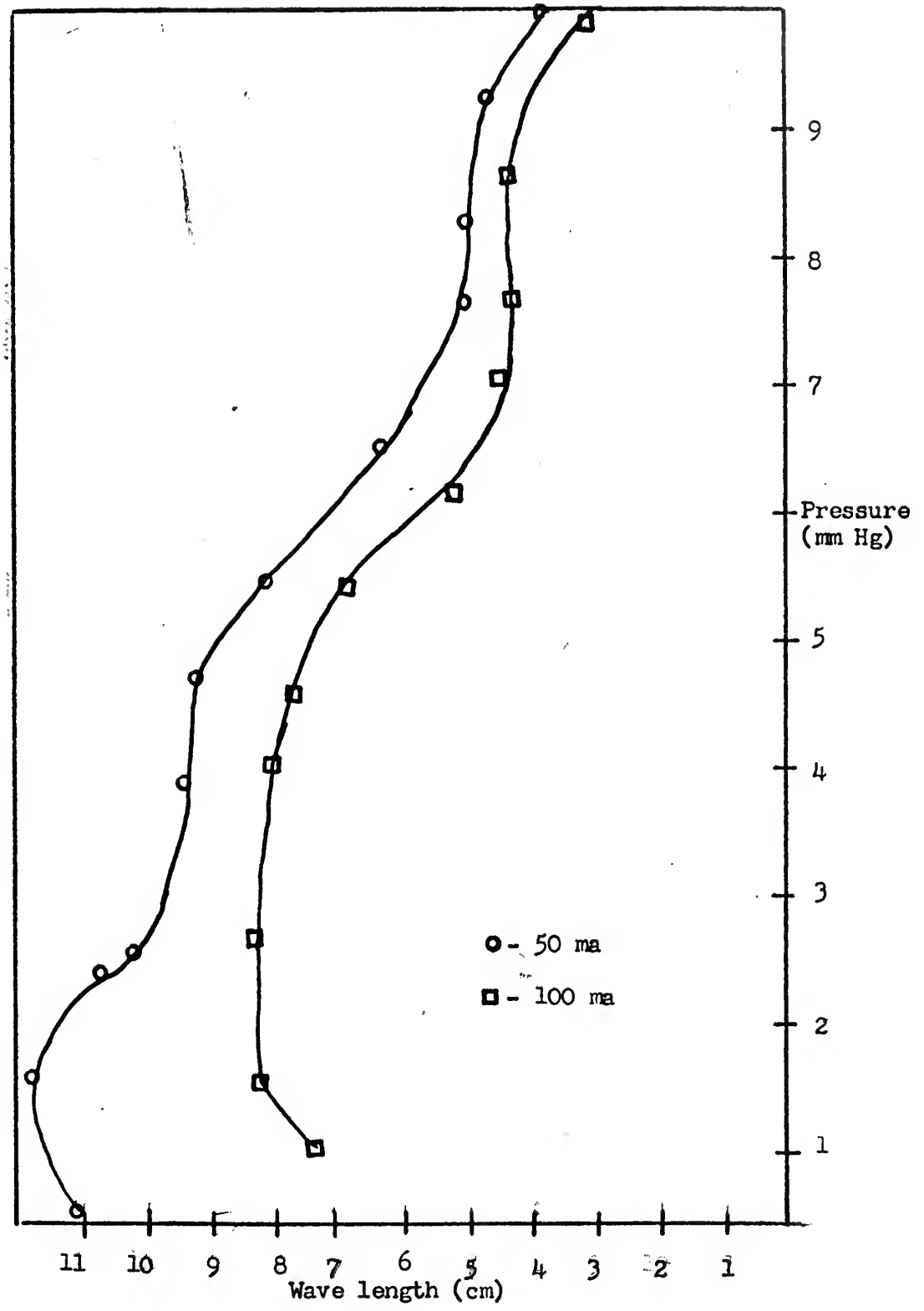


Fig. 19. Plot of Wave length vs. Pressure. Tube Radius - 31 mm

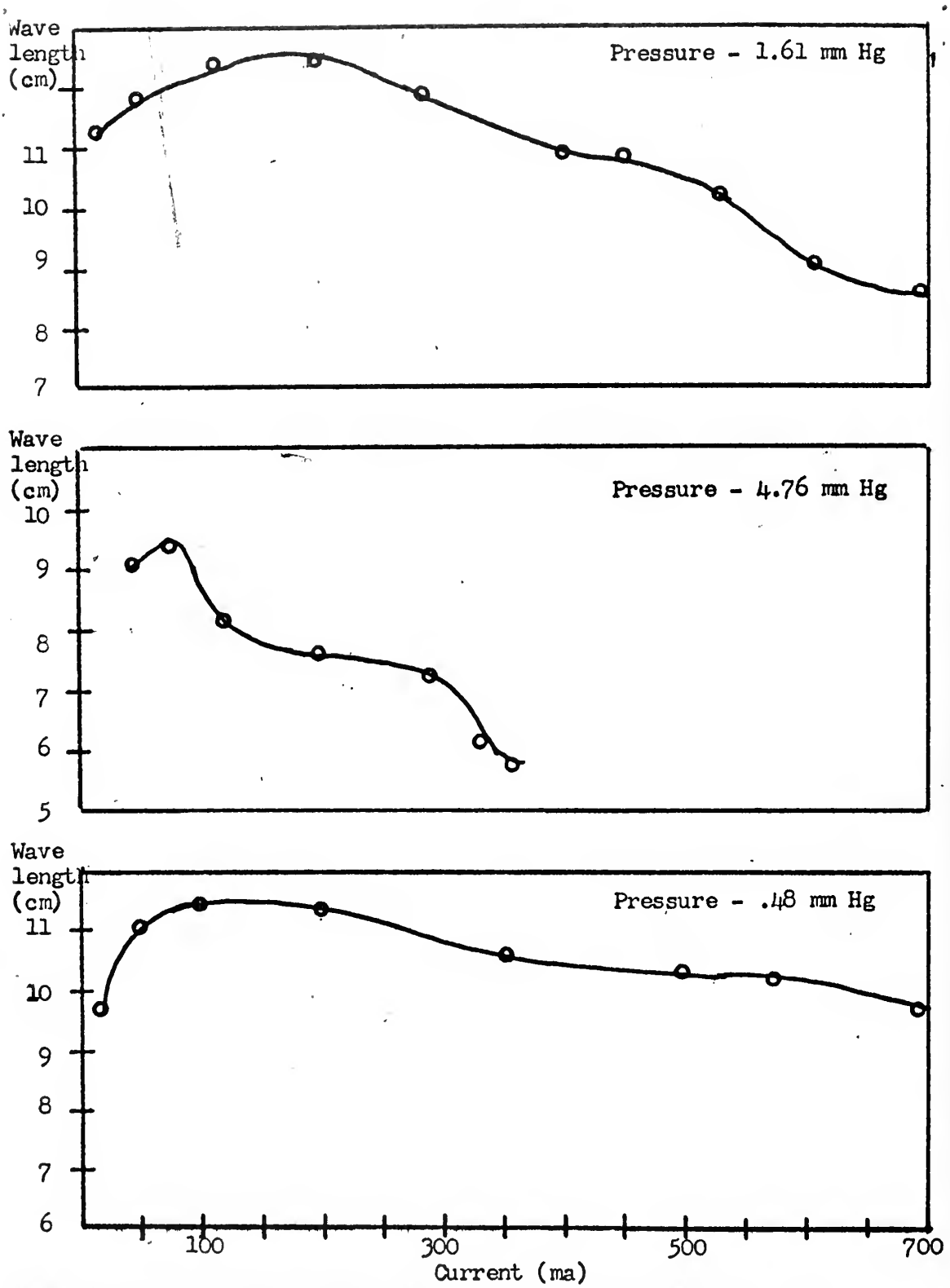


Fig. 20. Plot of Wave length vs. Current. Tube Radius - 31 mm

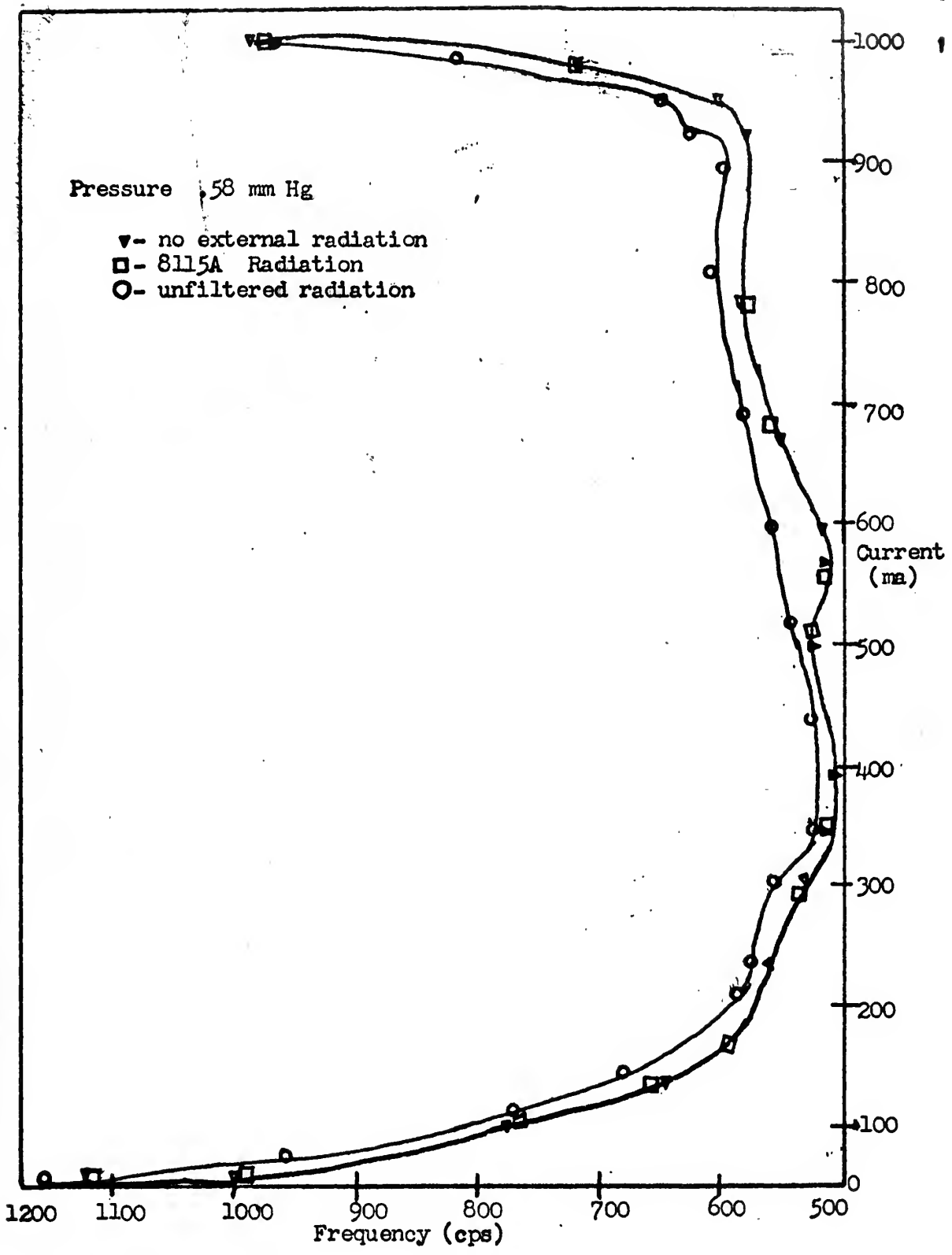


Figure 21. Frequency vs Current

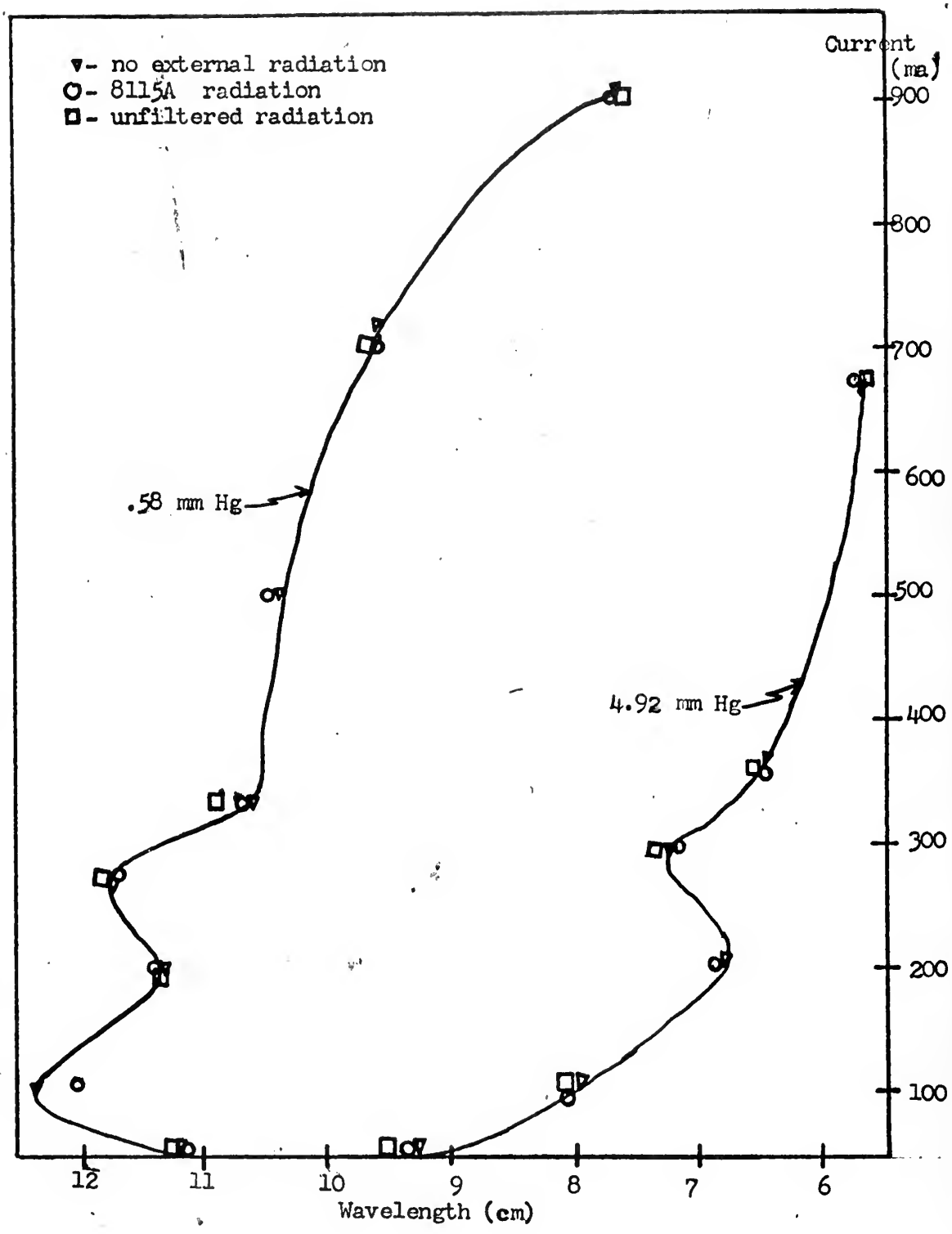
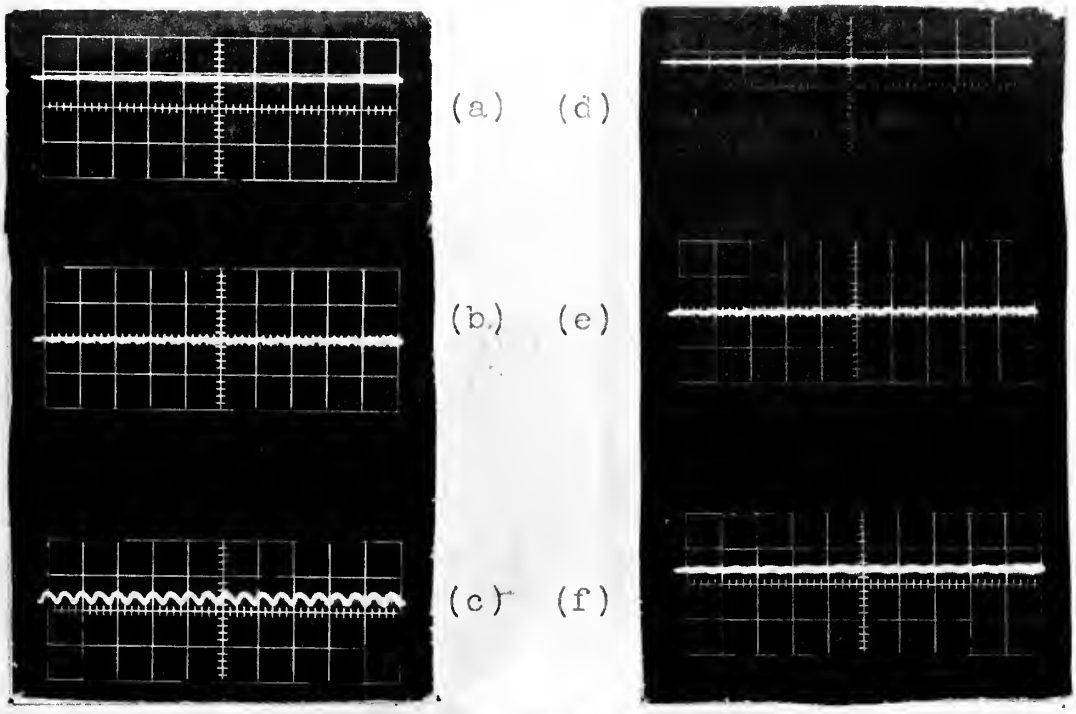


Figure 22. Wavelength vs Current



(a) Source Intensity I_1.

(b) Initial Conditions Prior to Irradiation. Current-30 ma.

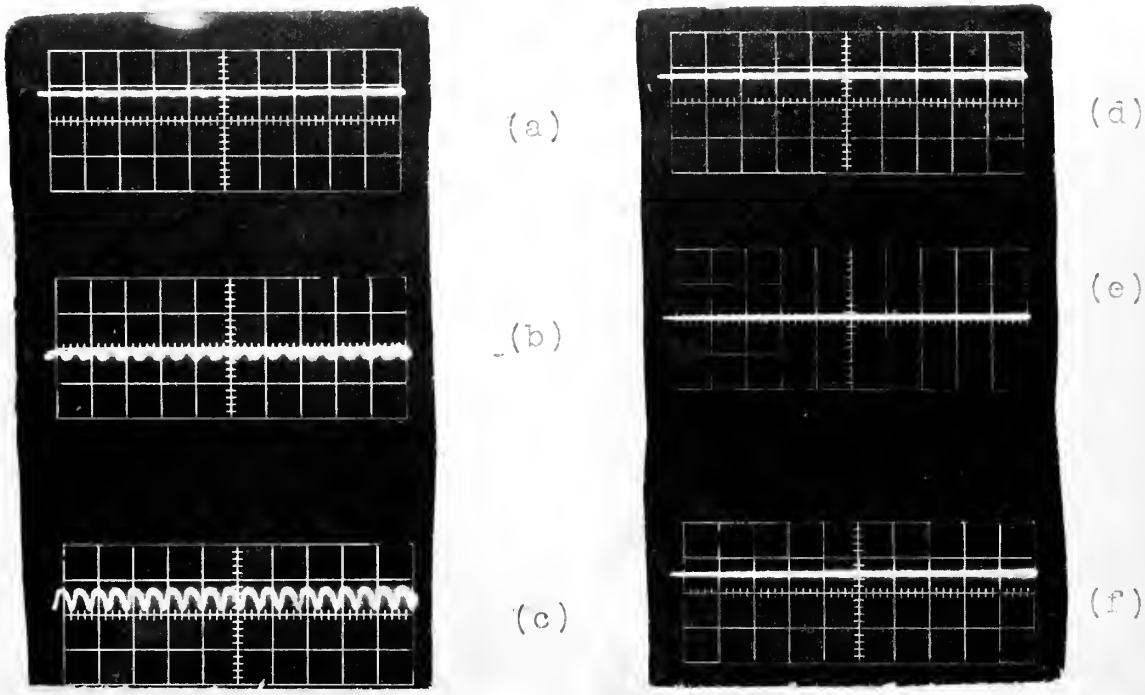
(c) Conditions After Irradiating with I_1.

(d) Source Intensity I_1.

(e) Initial Conditions Prior to Irradiation. Discharge Current-1400 ma.

(f) Conditions After Irradiating with I_1.

Figure 23 Oscilloscope Photograph Showing the bsorption of 8115Å Radiation by an gon Gl . Vertical Sensitivity- mv/cm; ensitivity 1 ms/cm



(a) Source Intensity I_1

(b) Initial Conditions Prior to Irradiation. Discharge Current-50 ma

(c) Conditions After Irradiating with I_1.

(d) Source Intensity I_2.

(e) Initial Conditions Prior to Irradiation Discharge Current-1900 ma.

(f) Conditions After Irradiating with I_2.

Figure 10 (Continued)

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A study of the argon glow discharge, to include determining the discharge conditions for maximizing the intensity of 8115A° radiation; observing the effects of external radiation and the absorption of the 8115A° line was conducted. Discharge tubes having diameters of 25 and 35mm, with gas pressures in the range of 0.5mm to 13.0mm Hg were used. The intensity of the 8115A° line was observed to increase with increase in current and pressure. A small increase in frequency of moving striations was observed when the glow discharge was irradiated with another argon glow discharge, but no increase was noted when the 8115A° radiation passed through the discharge. No changes were found in striation wavelength, amplitude or the discharge potential, when the main discharge was subjected to radiation composed of the entire argon spectrum, or to single line irradiation with 8115A°. The results of the absorption experiment indicate that there is more attenuation of the beam of 8115A° radiation when the main discharge is operated at low currents than at high currents. This may correspond to a denser population of $4s_{12}$ metastable atoms at low currents than at high currents, which would indicate a strong dependence of moving striations on metastable concentrations.

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